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THESIS

BROAD AREA WIRELESS NETWORKING VIA HIGH ALTITUDE PLATFORMS

by

Eric C. Cook

June 2013

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The wireless data technologies utilized in the commercial sector to meet the data distribution requirements of business and commercial telecommunications providers can be leveraged and adapted to meet the connectivity requirements of the DoD. By pairing these technologies with developing HAPs and their capabilities the potential for a long-range wireless broadband solution emerges.

This thesis evaluates broadband wireless data technologies in combination with High Altitude Platform (HAP) technologies. It proposes a network design concept to serve as a model for future research and the ultimate integration of HAPs into battlefield information architectures—bringing the concepts of network centric warfare ever closer to reality.

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BROAD AREA WIRELESS NETWORKING VIA HIGH ALTITUDE PLATFORMS

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LIST OF ACRONYMS AND ABBREVIATIONS

AESA	Active Electronically Scanned Array
AGL	Above Ground Level
AI&T	Assembly, Integration, And Test
AIS	Automatic Identification System
BACN	Battlefield Airborne Communications Node
BFT	Blue Force Tracking
BGAN	Broadband Global Area Network
CDMA	Code Division Multiple Access
CLIP	Common Link Integration Processing
COMINT	Communications Intelligence
COTS	Commercial Off The Shelf
CR	Cognitive Radios
CSMA/CA	Carrier Sense Multiple Access With Collision Avoidance
CSO	Combat Systems Operator
DAMA	Demand Assigned Multiple Access
DARPA	Defense Advanced Research Projects Agency
ELINT	Electronic Signals Intelligence
EPLRS	Enhanced Position Location Reporting System
FDMA	Frequency Division Multiple Access
FISINT	Foreign Instrumentation Signals Intelligence
FL	Flight Level
FMV	Full Motion Video

GEO	Geosynchronous
GEOINT	Geospatial Intelligence
GSM	Global System For Mobile Communications
HA	High Altitude
HAA	High Altitude Airship
HADR	Humanitarian Assistance And Disaster Relief
HALE	High Altitude Long Endurance
HAP	High Altitude Platform
HF	High Frequency
HUMINT	Human Resources Intelligence
IADS	Integrated Air Defense System
ICAO	International Civil Aviation Organization
IEEE	Institute Of Electrical And Electronics Engineers
IMINT	Imagery Intelligence
IMT	International Mobile Telecommunications
IOS	Iphone Operating System
IP	Internet Protocol
IRIS	Internet Routing In Space
ISIS	Integrated Sensor Is Structure
ISR	Intelligence, Surveillance And Reconnaissance
ITU	International Telecommunications Union
JP	Joint Publication
JXF	Joint Translator/Forwarder
LEO	Low Earth Orbit
LOS	Line Of Sight

LTA	Lighter-Than-Air
LTE	Long Term Evolution
MAC	Media Access Control
MASINT	Measurement And Signature Intelligence
MDA	United States Missile Defense Agency
MEO	Medium Earth Orbit
MIMO	Multiple Input Multiple Output
MOSA	Modular Open Systems Architecture
NASA	National Aeronautics And Space Administration
NATO	North Atlantic Treaty Organization
NOC	Network Operations Center
OFDM	Orthogonal Frequency-Division Multiplexing
ORS	Operationally Responsive Space
OSINT	Open-Source Intelligence
PTMP	Point To Multi-Point
PTP	Point To Point
QOS	Quality Of Service
RAT	Radio Access Technologies
RF	Radio Frequency
RNM	Range Nautical Miles
RPV	Remotely Piloted Vehicle
SA	Situational Awareness
SADL	Situation Awareness Data Link
SCADA	Supervisory Control And Data Acquisition
SIGINT	Signals Intelligence

SINCGARS	Single-Channel Ground And Airborne Radio System
SPF	Stratospheric Platform
TCDL	Tactical Common Data Link
TDMA	Time Division Multiple Access
TNT	Tactical Network Testbed
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UHF	Ultra-High Frequency
USAF	United States Air Force
USB	Universal Serial Bus
UTRA	Universal Terrestrial Radio Access
VOIP	Voice Over Internet Protocol
VTC	Video Teleconference
WLAN	Wireless Local Area Networks
WMD	Weapons Of Mass Destruction

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I. INTRODUCTION

A. BACKGROUND

The ever-increasing demand for broadband communications is a problem that many people are trying to solve. Commercial data providers continue to research ways to bring high-speed data communications to the customers in both cities and rural areas. Current infrastructures are a patchwork of terrestrial (e.g. wireless, cable, and traditional telephone lines) and satellite networks whose coverage does not span the entire globe or is difficult or prohibitively expensive to access. Out of this industry sector, the concept has grown of providing wireless broadband communications via High Altitude Platforms (HAPs). This concept has potential for solving some of the military's telecommunications challenges such as the need for rapidly deployable, high-speed data communications in austere or hostile environments. For the Department of Defense (DoD) to fully realize the idea of network centric operations[1], ubiquitous wireless data and communications is a key enabler, especially in remote and austere areas (i.e., the battlefield).

There is currently a multitude of technologies used by the DoD to distribute data across the battlefield. It is a patchwork of satellite communications, both commercial and DoD operated, line-of-sight (LOS) communications and legacy systems (e.g., Tactical Digital Information Links). These patchwork systems are complex (i.e., have many diverse interdependencies), hence difficult to understand, operate, maintain and troubleshoot, and they still do not cover the entire battlefield, as many coverage gaps and throughput problems exist [1]. A possible solution is the use of HAPs to meet those battlefield connectivity needs.

[1] For additional information on DoD's Network Centric Operations, see http://www.dodccrp.org/files/ncw_report/report/ncw_appendix.pdf.

High Altitude Platform (HAP) is a term used to describe an old concept that is gaining popularity for a new mission. A HAP is an aeronautical vehicle that is placed in the stratosphere at an altitude between 20–25 Km. The idea of lighter than air vehicles is certainly not new. It dates back to the Montgolfier brothers' invention of the hot air balloon in 1783 [1]. The idea is that the HAP is unmanned and stays aloft for a long period of time, and has the ability to keep station similar to a geostationary satellite (i.e., remain pseudo-stationary over a chosen geographical point above the earth's surface). A HAP is a vehicle that would carry a tailored payload for a specific mission. This thesis focuses on the mission of bringing long-range broad-area wireless networking to the battlefield.

B. OBJECTIVE

The objective of this thesis is to provide an overview of developing technologies to meet the goal of providing broad-area wireless networking to support military operations. The thesis addresses the development of HAP technology to facilitate this mission. Additionally, it explores the promising wireless technologies deployable aboard HAPs, factors associated with HAP operation, and potential missions and uses for HAPs.

This thesis proposes an idea for how to develop a HAP-based network capable of meeting the current and future bandwidth requirements of the warfighter and what technologies could facilitate this mission. This network design proposal is flexible, cost effective and adaptable to many different missions from current combat operations, intelligence, surveillance and reconnaissance (ISR), and humanitarian assistance and disaster relief (HADR).

C. RESEARCH QUESTIONS

This thesis examines the concept of broad-area wireless networking via HAPs. It examines various aspects of using HAPs across multiple missions. Since HAP technology is still in its infancy, much of the work is conceptual in nature. The research questions examined in this thesis include:

1. Primary Question

Given the growing demand for wireless data and communications in modern military operations, could HAPs provide a robust and cost effective solution to distribute wireless data across an area of operations?

2. Secondary Questions

- What existing or developing wireless technologies are best suited to develop a HAP based network?
- What services could be provided via HAPs?
- What advantages and disadvantages do HAPs have over space-based and terrestrially based solutions?
- How could HAPs be integrated into existing architectures and technologies?
- What are the advantages and disadvantages of selected HAP-based network designs?

D. SCOPE AND LIMITATIONS

The scope of this thesis is limited to past and current research regarding the development and use of HAPs for various services and missions. Much of the research regarding the use of HAPs for telecommunications missions stems from the commercial sector. A body of research exists regarding the potential use of HAPs to provide wireless data and telecommunications services in both urban and isolated locations. That research has been primarily directed toward providing commercial services. This thesis builds upon those ideas and examines the potential for military application. Military-based research is limited, but is ongoing and points to the potential the developments in HAP technology could bring to the military.

E. METHODOLOGY

The methodology applied to this thesis is a comprehensive literature review of recent and current research regarding HAPs and potential technological enablers for the application of broad-area wireless networking via HAPs.

- Examine HAP technology and evaluate its potential for military communications missions.
- Examine wireless technologies that could enable potential military applications.
- Determine and suggest potential network design and architectures that would be flexible and adaptable for military application.
- Review and propose potential mission sets for the convergence of HAP technology and wireless data transmission while viewing the subject through the lens of modern military missions and requirements.

F. THESIS ORGANIZATION

The thesis is organized into six chapters that are divided into specific subject areas. Chapter I is the introduction to the topic and provides the reader with the intended purpose of the thesis. Chapter II is an examination and overview of the history and current developments in HAP research and design. It provides the reader with a background and understanding of what HAPs are. Chapter III is a literature review of current and emerging wireless data technologies that could enable the utilization of HAPs to support military data transmission requirements. It offers the reader an overview of current and emerging technologies that are applicable to the potential network designs and mission sets discussed later in the thesis. Chapter IV is an exploration into potential network design architectures that have military application and could provide a vast capability for current and future operations. Chapter V offers a vision for missions that HAPs could support or enhance. It focuses on services and missions that could be enabled and enhance through the use of HAP technology. It is intended to provide a vision and spark the creativity of the reader to examine potential uses for HAPs. Chapter VI is the conclusion of the thesis and provides recommendations for deeper study and research areas to enable the further development of HAP-based solutions.

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II. HIGH ALTITUDE PLATFORMS

A. INTRODUCTION

Much of the wide area wireless data transmission research involves the terrestrial platforms that provide the infrastructure for distributing wireless signals. The best example of those is the commercial cell phone tower system: it provides the infrastructure upon which the high-speed wireless equipment is mounted. Building, maintaining and protecting a ground-based network of towers in underdeveloped, austere, or battlefield areas is either cost prohibitive or tactically unfeasible. Many researchers look toward aero systems because they can be comparably inexpensive, require little ground infrastructure, and be rapidly deployable. High Altitude Platforms offer the potential to meet all of those requirements as well as provide other benefits over ground-based wireless networks.

High Altitude Platform (HAP) or Stratospheric Platform (SPF) are some of the terms used to describe an old concept (i.e., use of lighter than air vehicles to provide long endurance or large area coverage) that is gaining popularity for a new mission. Another term that has gained popularity is High Altitude Long Endurance (HALE). All of these terms are used to describe an aeronautical vehicle that is placed in the stratosphere at an altitude of 17–22 km. For the purpose of this thesis, the term High Altitude Platform (HAP) is used.

Lighter than air vehicles are certainly not new; they date back to the Montgolfier brother's invention of the hot air balloon in 1783 [1]. Several things differentiate old style balloons from current HAP designs; they are: (1) a HAP is unmanned, (2) it stays aloft for extended periods of time (days, months, even years), and (3) it remains relatively stationary. A HAP has characteristics similar to a geostationary satellite: it remains pseudo stationary over a chosen geographical point on the earth's surface while performing its mission. An advantage a HAP has over a satellite is its ability to maneuver--if needed--and reposition to a more advantageous or safe location. Additionally, a HAP is able to provide coverage to wide areas while requiring far less infrastructure compared to the build out of a new terrestrial network or the development and operation of a satellite network [1].

B. HISTORY OF DEVELOPMENT

HAPs are certainly not new. From the invention of the lighter than air balloon, military thinkers have been devising ways to employ the technology to support battlefield operations. Some of the earliest work in utilizing balloons for military communications date back to the 1790s [2]. During the American Civil War, Union and Confederate forces experimented with the use of both tethered and free balloon systems for reconnaissance and artillery spotting. The success and tactical advantage that these systems provided did not go unnoticed. As radio communications emerged, the application of lighter than air vehicles for military communications matured. During both world wars, the radio served as the primary method of communications for commanders. To facilitate longer range (i.e., beyond line of sight) communications, several nations utilized various balloon systems as well as dirigibles (Figure 1) as communications nodes. The U.S. Navy used dirigibles for both communications and for carrying and launching reconnaissance aircraft [2].

Figure 1. USS *Los Angeles* (ZR-3) Flying over southern Manhattan Island, New York City, circa 1924–1932. From [3].

Seeing the utility in communications via high altitude platforms, the National Aeronautics and Space Administration (NASA) began experimenting with the idea of communications satellites during the 1950s. The first satellites launched for this purpose were actually large balloons. On 12 August 1960, NASA launched the ECHO 1 (Figure 2). It was a large Mylar balloon with an aluminized surface designed to act as a passive communications satellite. Using its reflective surface, NASA experimented with bouncing radio and television transmissions off of it to extend communication ranges. It also carried a payload of radios and solar panels used for telemetry tracking. In 1964, the ECHO 2 was launched with an expanded radio payload [2].

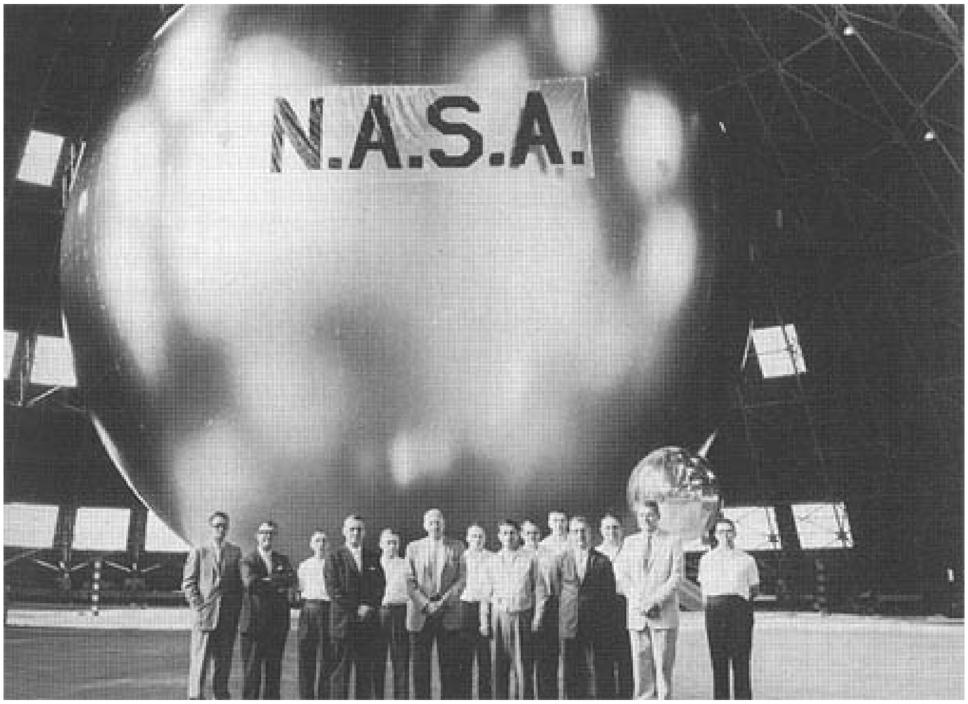

Figure 2. Echo 1 sits fully inflated at a Navy hangar in Weeksville, North Carolina. From [4].

The use of lighter-than-air (LTA) vehicles for military application is an idea that continues to surface. In a 1974, a report by the Air Force’s Cambridge Research Laboratory shows the origins and current direction of these programs.

> As will be seen shortly, the LTA relay platform concept has special relevance to the communication demands of modern tactical warfare. Those demands have forced the development of high-capacity, multi-mode transmission systems to replace the inadequate ground-netted systems currently in use. The SEEK STAR system, which is being developed by the 478T Combat Theater Communications Program Office of the Electronic Systems Division, USAF, is a multi-mode system and will serve as the basic reference system in this report.
>
> These new communications systems rely heavily on airborne relay units to achieve instantaneous point-to-point message of data transmittal. The “primary” airborne relays employed in these applications are carried aloft on spacecraft placed in synchronous earth orbit, such as those used in the Defense Satellite Communications System. “Secondary” or “backup” airborne relays

> are carried aboard aircraft, which, in this case serve as gap-filler satellites. With respect to the latter category, the trend in recent years has been toward unmanned air-borne relay aircraft for reasons of cost effectiveness, reduced crew vulnerability, increased station-keeping time, etc. The HALE RPV (High-Altitude, Long Endurance, Remotely Piloted Vehicle) development has been undertaken by the Aeronautical Systems Division to satisfy this trend. Aircraft built under the HALE program are expected to fly at altitudes as high as 50,000 ft (15.24 km) for up to 24 hours [5].

The report outlines much of the origins of the current HALE programs along with identifying many of the advantages that a HAP has over satellite-based communications. Some of the key themes addressed are that even though HAPs were designed as back up or gap-filler systems, they inherently had several advantages. The identified advantages were cost savings and reduced sophistication in design and production because the HAP systems do not have to meet “space-qualified” specifications, increased jam resistance because of stronger signal strengths, and rapid payload adjustability and upgrade. The primary advantage noted was the capacity for rapid deployment because it could take years to develop and launch costly space based systems, whereas HAP systems could be launched and on station in a matter of days or hours [5].

C. CURRENT PROGRAMS

HAP development over the years has been a stop and start affair. With shifting priorities and resource limitations, research and development of tactically field-able platforms and technologies has been slow. The grand vision laid out by the Cambridge Laboratory in 1974 has yet to come to fruition. That does not mean the research has stopped; HAP programs are under development domestically along with competing technologies from foreign governments and commercial entities. The rest of this chapter provides a survey of notable HAP developments, ongoing programs and military research.

1. StratXX AG

StratXX is a Swiss company that is trying to commercialize HAPs with an innovative marketing strategy that starts with its flagship product the X-Station [6]. The X-Station is an unmanned HAP intended to stay aloft for up to a year. Notable specifications of the design are an intended station altitude of 21K meters, a payload capacity of 100 kg, and 1000 watts of onboard power for payload requirements. They also developed a series of lower altitude airship-based products designed to work in conjunction with the X-Station to provide a variety of services to wide geographical areas--see Figure 3. Services provided by the StratXX product line are: (1) high speed data, (2) voice data and video, (3) television on demand, (4) fixed and mobile convergence, (5) localization and tracking, (6) last-mile solutions, and (7) homeland security [7].

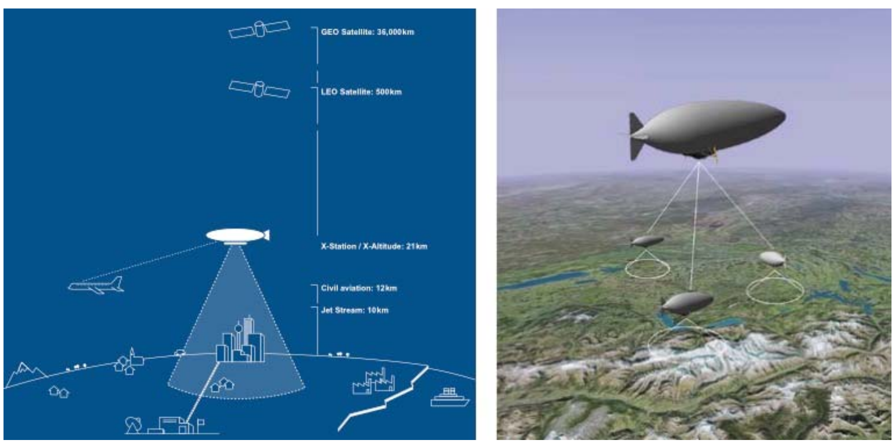

Figure 3. StratXX X-Station altitude and illustration. From [7].

2. CAPANINA

The CAPANINA project (November 2003 to January 2007) focused on the development of low-cost, high-speed broadband data connectivity via HAPs to users in geographically remote areas and on trains. There were three trials demonstrating the potential for wireless network service delivery. Although limited in scope, the trials demonstrated several key technologies. Broadband wireless links utilizing the IEEE 802.11b technology standard, and the first known

1.25 Gbits/s HAP to ground data link via optical laser [6]. The CAPANINA service delivery model (see Figure 4) is very similar to other proposed data service delivery models within the field of study.

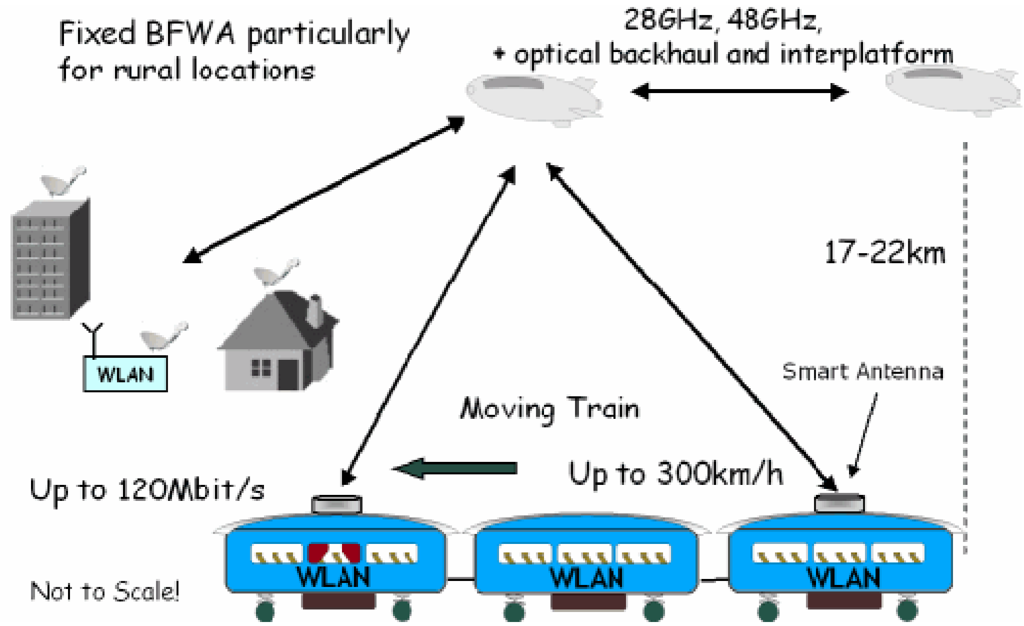

Figure 4. CAPANINA Project Service Delivery Model. From [8].

3. Space Data Corporation

Space Data Corporation is a U.S.-based company that provides several solutions for wireless data delivery to remote areas. Unlike the previous example, Space Data Corporation is an active corporate venture with currently fielded solutions available to the commercial and the military markets. Its primary market is providing telemetry and monitoring services to the oil and gas industry. This provider recognized the lack of maturity in the HAP industry and chose to use free flying balloons (e.g., weather balloons) that have been in service for many years. The balloons are launched every 8–12 hours from launch sites close to the desired coverage area with the intent of providing 24-hour coverage. The balloons are launched with a recoverable payload and operated at an altitude of 24K–30K meters to provide a coverage area approximately 540 km in diameter [6].

Space Data Corporation has two product lines, (1) SkySite™—geared toward commercial monitoring for the oil and gas industry, and (2) StarFighter™—intended for military and governmental users. The SkySite™ platform utilizes Motorola 2-way packet data technology operating in their licensed frequency band of 901–940 MHz. The SkySite™ provides 24/7 data connectivity for supervisory control and data acquisition (SCADA) communications, pump controller monitoring, kW meter reading, compressor/tank alarming, oil pipeline monitoring and more [6]. StarFighter™ carries a military UHF repeater operating from 225–375 MHz. This payload extends the reach of standard military 2-way radios from a terrestrial line of site limitation of approximately 10 miles to nearly 500 miles. The repeater payload is customizable for various missions (e.g., intelligence, surveillance, and reconnaissance (ISR)). The StarFighter™, shown in Figure 5, is limited by weight restrictions and battery capacity, but can provide valuable ad-hoc tactical network extensions with minimal ground support [9].

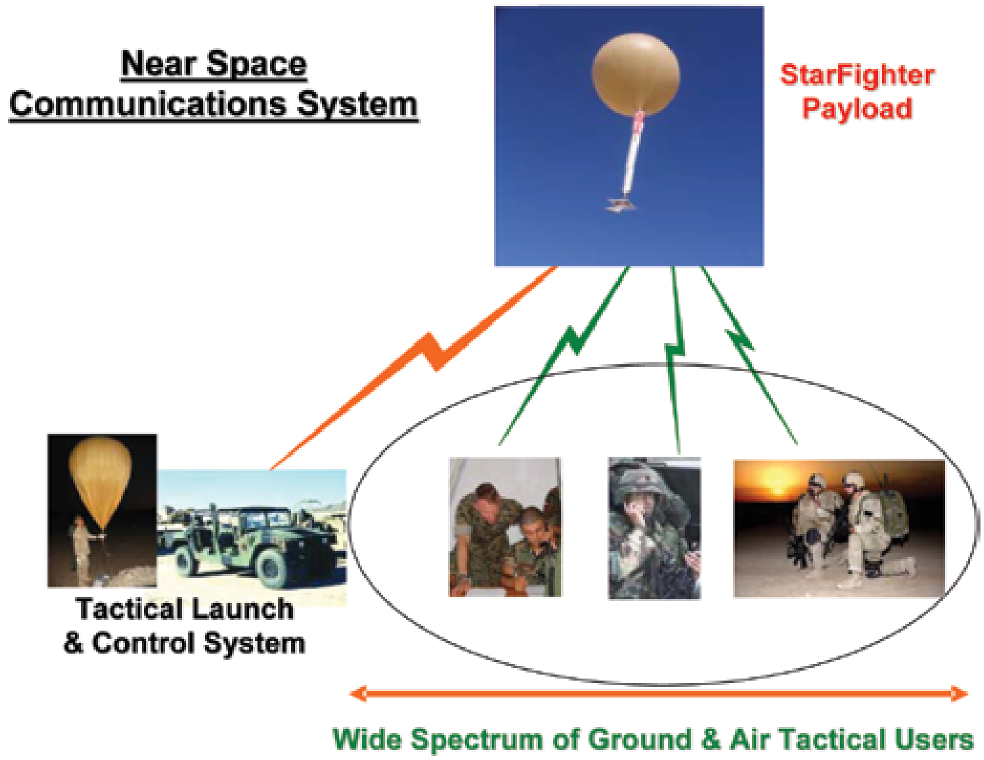

Figure 5. Space Data's SkyFighter™ platform. From [9].

4. Lockheed Martin

In 2003, a program funded by the United States Missile Defense Agency (MDA), known as the High Altitude Airship (HAA) program came into existence. The program teamed Lockheed Martin, Boeing, and WorldWide Aeros together to take part in the concept development phase (Phase 1). This phase concluded with the selection of an initial design. The MDA choose Lockheed Martin as the sole contractor to move into Phase 2, the critical design review. Since then, Lockheed Martin is funded to develop a HAA to meet the following specifications: (1) a one month mission life, (2) a 19.8K meter operating altitude, (3) a 10 Kw payload power, and (4) a payload capacity of 4000 pounds capable of carrying an active electronically scanned array (AESA) radar and associated equipment [6].

The project continues with Defense Advanced Research Projects Agency (DARPA) funding and is incorporated into the Integrated Sensor is Structure (ISIS) program.

> The Integrated Sensor is Structure (ISIS) program is developing a sensor of unprecedented proportions that is fully integrated into a stratospheric airship that will address the need for persistent wide-area surveillance, tracking, and engagement for hundreds of time-critical air and ground targets in urban and rural environments. ISIS is achieving radical sensor improvements by melding the next generation technologies for enormous lightweight antenna apertures and high-energy density components into a highly integrated, lightweight, multi-purpose airship structure - completely erasing the distinction between payload and platform [10].

The ISIS program and HAA program are integrated; thus, the design requirements for the HAA have continued to change. Most recently, as part of the spiral development cycle toward the goal of the full capacity HAA, Lockheed Martin began flight-testing its High Altitude Long Endurance–Demonstrator (HALE-D). The HALE-D is a proof of concept platform for the demonstration and the testing of technologies, systems and designs that will eventually find their way into the full-scale HAA [11]. The HALE-D, seen in Figure 6, is the next step in producing long endurance HAPs to fulfill U.S. defense requirements. The benefits statement from the U.S. Army Space and Missile Defense Command/Army Forces Strategic Command factsheet on High Altitude efforts offers a good conclusion and vision for the continued development of HAPs.

HA platforms will provide a much needed persistent 24/7 capability for surveillance and communication platforms to see over-the-horizon for theater and homeland defense operations. Presently, HA platforms are limited to short duration missions of about 24 hours, and then they must come down and be prepared for their next mission. The LTA platforms will provide an unmanned airship capable of carrying different payloads for durations greater than 30 days. The HA platforms will station keep within a two km radius at greater than 60,000 feet altitude providing a 325 mile line-of-sight capability to horizon. With the capability of station keeping and long duration, this can provide persistent communications and Wide Area Surveillance (WAS) [12].

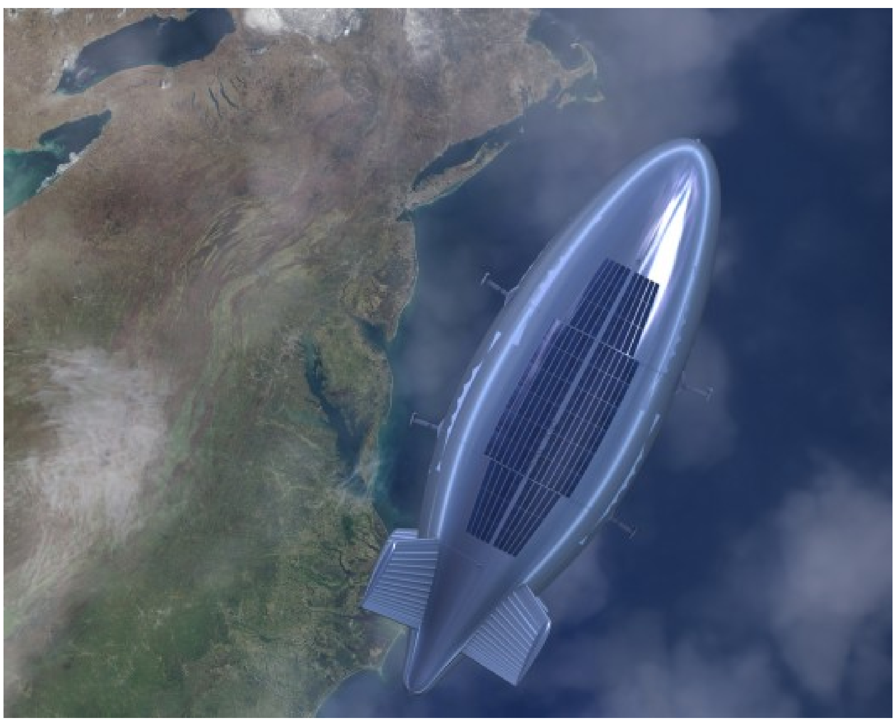

Figure 6. Lockheed Martin HALE-D artist’s impression. From [11].

D. SUMMARY

HAPs are evolutionary aerial vehicles whose origins are hundreds of years old. HAPs are a convergence of old and new technology. They incorporate LTA concepts with modern unmanned aerial systems. HAPs have the potential to change the way data and communications are distributed across the battlefield. The advances by the HAA and ISIS programs are setting the stage for future developments and mission adaptations. The following chapters discuss additional technologies and network design considerations for the adaptation of HAPs to bring persistent wide area data and communications connectivity to the battlefield.

III. WIRELESS PROTOCOLS, EQUIPMENT AND REGULATIONS

The International Telecommunications Union (ITU), in anticipation of HAP development, has allocated specific frequency bands for HAP use. These include the 47 GHz, 48 GHz, 31 GHz, 28 GHz, 27 GHz, and 2 GHz bands. The 6 GHz band has also been under consideration for commercial use [6]. There are also a number of unlicensed and military frequency bands available for use that offer potential for military application. Because of regulatory restrictions and atmospheric effects on propagation, the frequencies that show the greatest potential for use in the HAP-to-end user link are below 10 GHz. This is primarily due to atmospheric effects on propagation that will be explained in chapter IV.

The ITU created a set of requirements for mobile communications known as International Mobile Telecommunications-2000 (IMT-2000) and International Mobile Telecommunications-Advanced (IMT-Advanced). To provide the level of service required by military users, only the technologies that fall under the umbrella of the IMT-Advanced standards are discussed in this thesis. The IMT-Advanced standard is widely known as “4G” in the commercial marketplace. This chapter discusses candidate technologies employing the IMT-Advanced standards as well as complimenting technologies. Additionally, a brief overview of advances in radio equipment and antenna design is presented along with an overview of commercially available technologies that are potential facilitators of HAP-based networking.

A. IMT-2000

In the mid-1980s, the International Telecommunication Union (ITU) began working on a set of standards to improve wireless mobile telecommunications systems. That work resulted in third generation technology or 3G networks. It operates between 400 MHz and 3 GHz. The major advantages realized by the adoption of International Mobile Telecommunications (IMT)—2000 standard is the simplification of the mobile telecommunications marketplace by creating a global set of standards to foster greater interoperability. The standard set a minimum performance requirement of 2 Mbits/s for stationary or slow moving users and 348 Kbit/s for mobile users traveling at higher speeds such as train and automobile passengers. That was a vast improvement over previous generation systems. The IMT-2000 also worked to improve compatibility by designating five radio interface types along with three different access technologies; they are Time Division Multiple Access (TDMA), Code Division Multiple Access (CDMA), and Frequency Division Multiple Access FDMA [13].

While many advances have occurred in “3G” technologies over the past decade to greatly increase the throughput of these systems over the original standard, 3G’s capacity may be limited for military application. To provide the most robust wireless networking service possible from HAPs, most research is shifting to the next generation technologies.

B. IMT-ADVANCED

The ITU developed a follow-on standard to ITM-2000 known as IMT-Advanced.

> International Mobile Telecommunications-Advanced (IMT-Advanced) systems are mobile systems that include the new capabilities of IMT that go beyond those of IMT-2000. Such systems provide access to a wide range of telecommunication services including advanced mobile services, supported by mobile and fixed networks, which are increasingly packet-based.
>
> IMT-Advanced systems support low to high mobility applications and a wide range of data rates in accordance with user and service demands in multiple user environments. IMT Advanced also has capabilities for high quality multimedia applications within a wide range of services and platforms, providing a significant improvement in performance and quality of service. [14]

Two of the key components of the IMT-Advanced standard are the targeted data rates and the focus on packet based communications. The targeted goals for IMT-Advanced are a peak throughput of 100 Mbits/s for highly mobile users and up to 1 Gbits/s for low mobility or static users [14]. This capability is key to providing the foundation to a tactically feasible military application of HAPs.

Because of the lack of commercially viable HAP solutions, the ITU has not made any HAP specific frequency spectrum allocations for these technologies. The 6 GHz band was previously considered for IMT-2000 use as well as the unlicensed 5 GHz spectrum widely used for Wireless Local Area Networks (WLAN) [6].

The ITU has identified two specific technologies that meet the criteria of the IMT-Advanced requirements. They are the Long Term Evolution–Advanced (LTE-Advanced) and Worldwide Interoperability for Microwave Access IEEE 802.16m-2011 (WiMAX 2) standards. Figure 7 shows the progression of the various technologies toward the goal of IMT-Advanced. Both of these standards are competing in the commercial marketplace for acceptance as the global standard for high-speed mobile data transmission. It appears that LTE-Advanced leads in the commercial cellular communications marketplace, but ultimate market domination remains to be achieved.

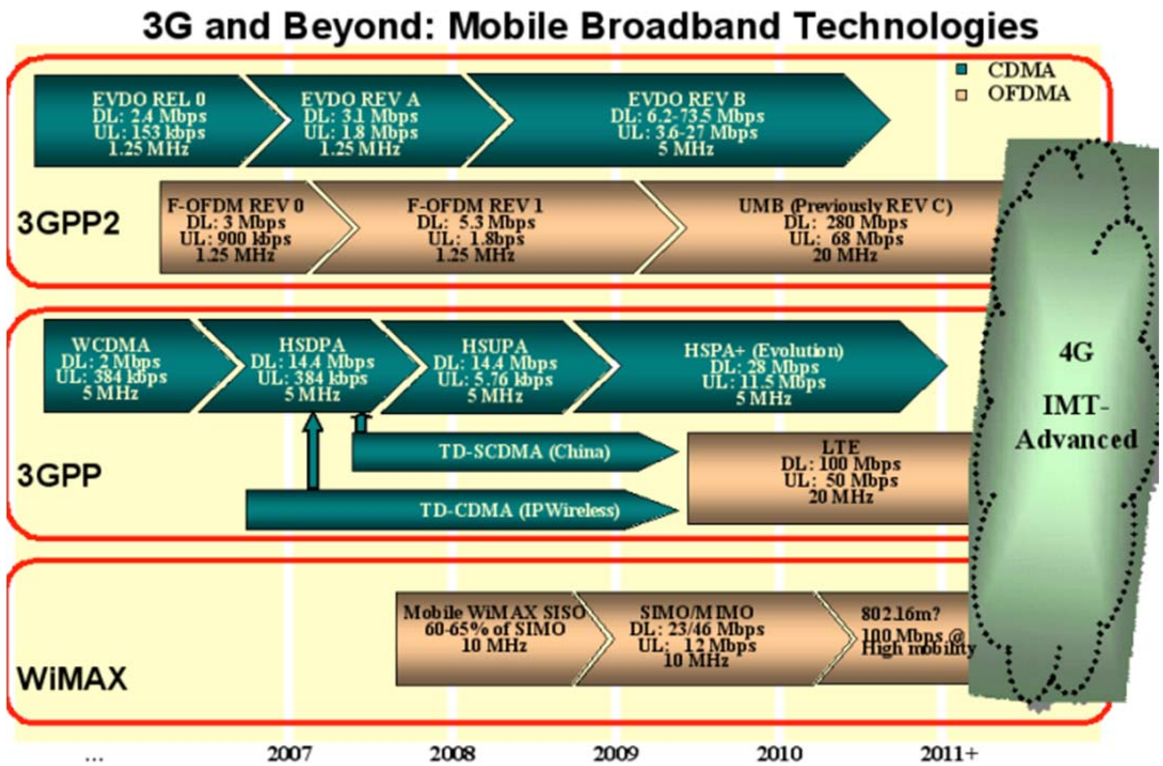

Figure 7. The path to 4G. From [15].

1. LTE-Advanced

LTE-Advanced is an incremental upgrade to existing LTE technologies that are currently deployed in the commercial marketplace. Because of this, it appears that LTE-Advanced will become the technology of choice among commercial providers. LTE-Advanced features several performance improvements over the existing technology. These features are carrier aggregation, enhanced multi-antenna support, improved support for heterogeneous deployments, and relay capabilities [16].

a. Carrier Aggregation

Carrier aggregation means that multiple carrier frequencies are bonded together to improve bandwidth and throughput. The IMT-Advance requirement calls for a minimum bandwidth of 40 MHz. Due to carrier aggregation, LTE-Advanced and WiMAX 2 both have the capacity for up to 100 MHz of transmission bandwidth [16]. Bandwidth is critical in wireless data transmission: the more bandwidth available, the more data that can be transmitted over those channels. Bandwidth is analogous to the diameter of a water pipe; the wider the pipe, the more water can be moved.

b. Enhanced Multi-antenna Support

Enhanced Multi-Antenna support is critical to gain the performance advantage of LTE-Advanced. Multi-Antenna support already existed in previous generations of LTE, but LTE-Advance extends those capabilities to improve both the uplink and downlink signal multiplexing. The downlink spatial multiplexing is expanded to handle up to eight transmission layers simultaneously, while the uplink is expanded to handle up to four. This increases downlink data capacity by allowing for up to eight carrier frequencies and their associated bandwidth to be aggregated for enhanced download speeds and throughput capacity. This provides for higher throughput for bandwidth intensive services like streaming video and larger file downloads. The enhanced capacity of the downlink is based on the fact that LTE-Advanced was designed as a mobile technology [16].

c. Improved Support for Heterogeneous Deployments

Improved support for heterogeneous deployments is a term that refers to the ability for network operators to deploy different levels of cells within an area. Seen in Figure 8, a cell refers to specific areas that an antenna is designed to cover. Typical terrestrial network design is based on Macro-cell coverage (e.g., Legacy mobile phone networks). Macro-cells are large area cells. In legacy mobile phone network designs, geographic areas are broken up into cells that are covered by a grid of cell towers. In heterogeneous deployments, cells of differing power and coverage overlap to provide the end-user a more robust service experience. In more simplistic terms, this allows for the deployment of Pico-cells within the network environment. The Pico-cells are smaller, lower powered cells that provide enhanced coverage in areas on the outer edge of the Macro-cell sites or where Macro-cell coverage is degraded such as in underground subway stations or dense urban areas. The Macro-cells and Pico-cells would coordinate frequency reuse schedules to minimize interference and enhance coverage [16]. In Figure 8, the large tower symbols represent the Macro-cell towers that provide the overarching coverage. The smaller tower symbols are examples of Pico-cells used to provide improved signal coverage.

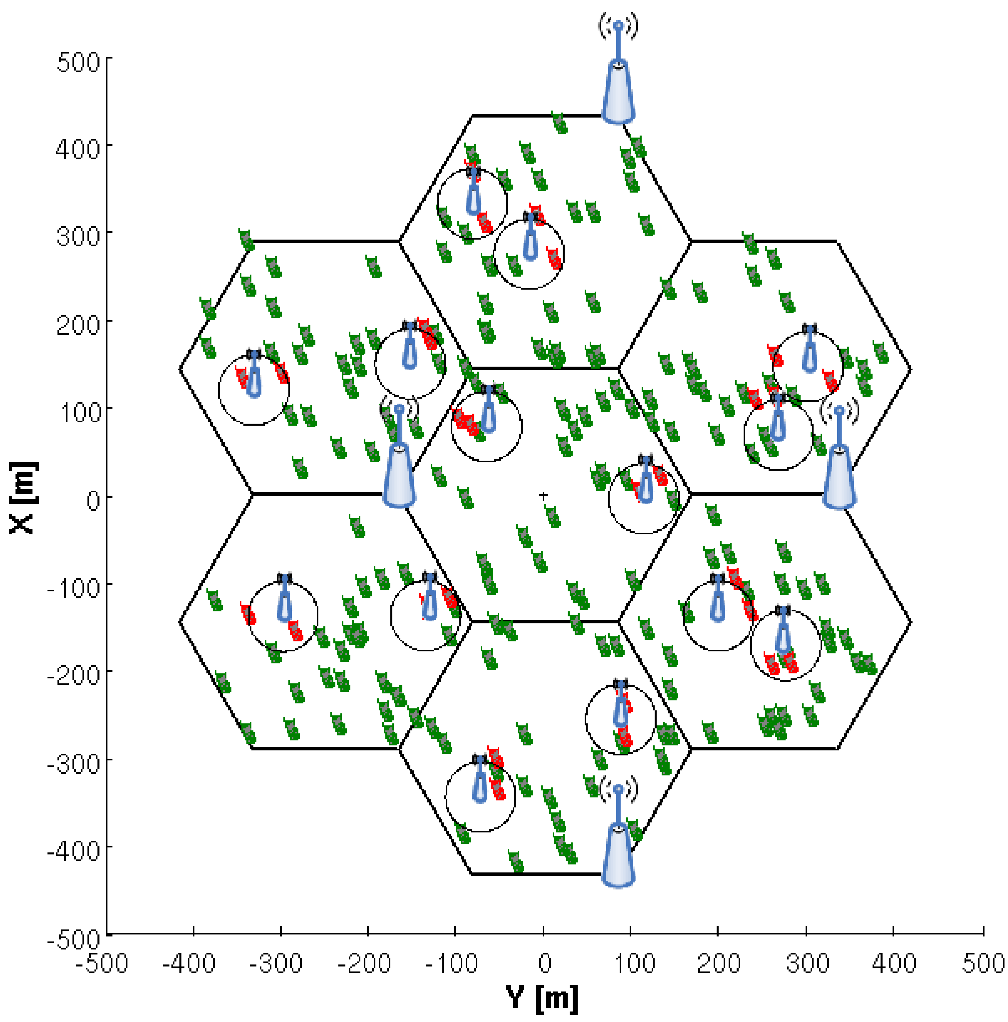

Figure 8. Example of Pico-cells inside Macro-cell coverage. From [17].

d. Relay Capability

The relay-cell acts in a very similar fashion as the previously mentioned Pico-cell. The key difference is that the Relay-cell does not need direct connectivity to the provider's back-haul network. A back-haul network is the network a provider uses to connect each of its broadcast towers to the main telecommunications infrastructure. This is typically done with a hard-wired connection such as fiber optic cable or a dedicated microwave link. In contrast a Relay-cell would use its wireless connection to the Macro or Pico-cell for back-haul purposes while extending the network. The transition would be seamless for the end-user and offer the capability to extend the network into problematic areas [16].

While LTE-Advanced seems to be a great leap forward for commercial providers, it may not be the technology of choice for HAP deployment. An important consideration for choosing a technology is the conditions where it must operate. One such consideration is the potential interference with existing terrestrial networks. In a disaster relief scenario, a HAP based LTE-Advanced network could cause significant interference to recovering terrestrial infrastructures because of improperly reused frequencies. Its use would be further hampered by the need for interference avoidance planning. Any HAP based system would need to have a minimal impact upon existing terrestrial networks. This is also a consideration in military operations; areas of operations often contain urban areas with local populaces that rely upon existing telecommunications systems. Military systems need to deconflict with existing local systems to prevent interference, and reduce the potential for local systems to interfere with the military network.

2. WiMAX 2

WiMAX 2 is the commonly used term for the recently ratified IEEE 802.16m-2011 standard. WiMAX 2 is an evolutionary advance in technology based upon the currently deployed 802.16e standard. It provides a substantial performance increase over the current standard and has many features in common with the LTE-Advance standard previously discussed. 802.16 was originally designed around a common Media Access Control (MAC) protocol. WiMAX’s initial implementation used a single carrier technology with a designed operating range in the frequency spectrum from 10 to 66 GHz. It was intended for static point-to-point links without consideration of multi-path propagation. As the technology matured, support expanded to include lower frequencies from 2 to 11 GHz. The technology became widely adopted with the 802.16e standard that extended the physical and MAC layers to combine both fixed and mobile users. The standard supported data rates of up to 15 Mbits/s to mobile users operating at speeds up to 100 km/h [6].

Because of its intended design purpose of providing broadband wireless access and its wide frequency operating range of 2 to 66 GHz, WiMAX is positioned as a nearly ideal option for HAP deployment [6]. Additionally, the performance and capability enhancements offered by the latest 802.16m-2011 revision position WiMAX as the better alternative over LTE-Advanced for HAP use.

The WiMAX 2 standard provides a vast improvement over 802.16e by improving not only its range and throughput, but also additional features that are in line with similar advances made in the LTE-Advanced standard. Some of the key enhancements incorporated into the standard include multicarrier operation, support for Femto-cells and self-organizing networks, Multi-Radio Access Technologies (Multi-RAT) operation and handoff, Multi-Radio coexistence support, and multi-hop relay-enabled architecture [18].

a. Multicarrier Operations

Multicarrier operations in the WiMAX 2 standard again are very similar to those in the LTE-Advanced standard. The WiMAX 2 standard supports carrier channel bonding of up to 4 channels on the downlink and 2 channels on the uplink. This allows for up to 100 MHz of bandwidth dedicated to the downlink.

An interesting feature incorporated is the ability to integrate carriers of differing bandwidths that can be either contiguous or non-contiguous. It also supports multi-carrier integration of carrier signals from different frequency bands and different duplexing modes. This allows for the simultaneous use of bidirectional and broadcast only carrier frequencies, hence permitting application-based bandwidth tailoring. For example, bidirectional carrier signals could be used for Voice over Internet Protocol (VOIP) applications where the broadcast only carrier could be used to push streaming video feeds. By allowing a mix of frequency bands and mixed carrier types, signal and bandwidth allocation could be tailored for specific user needs [18].

b. Femto-cells

Femto-cells are low power base stations that are usually deployed inside buildings or other areas with weak or gapped macro-network connectivity. These cells are connected back to the main network via a local broadband connection. Previous Femto-cell deployments required specialized dual-mode user equipment to switch between the macro network and the smaller cell. WiMAX 2 removes this requirement by allowing the user equipment to seamlessly switch between the two allowing for very high data rates and service continuity as users move between macro-network coverage areas and smaller cells such as Pico-cells, Femto-cells and non-WiMAX 2 hotspots. This is accomplished through network self-organization.

c. Self-organizing Networks

In self-organization, the network self-configures to allow plug and play installation of additional network nodes. Self-organizing networks are also referred to as mesh networks. These terms are often used interchangeably to describe a network that is decentralized with interconnected nodes that route and relay information to other nodes. It allows for rapid and automated reconfiguration and compensation for node movements or failures. The self-optimization of the network greatly reduces operator workload through autonomous optimization of the network to insure service availability, quality of service (QoS), network efficiency, and throughput [18].

This provides a tremendous advantage for military or disaster relief applications where network topology may rapidly change. A self-organizing network allows for nodes to move and be added or removed with convenience. The network would adapt to maintain connectivity.

d. Multi-radio Access Technologies

WiMAX 2 supports multi-radio access technology (Multi-RAT) integration and handoff. This allows network designers to implement network designs with different radio access technologies depending upon design needs. WiMAX 2 is designed to work seamlessly with IEEE 802.11 Wireless Fidelity (WiFi), Global System for Mobile Communications (GSM), Universal Terrestrial Radio Access (UTRA), Evolved Universal Terrestrial Radio Access (E-UTRA), and Code Division Multiple Access (CDMA2000) systems [18]. This exceptional capability allows network designers to incorporate existing wireless infrastructures and equipment into a new network by utilizing multi-radio coexistence support. Multi-radio coexistence is where different radio technologies are operating simultaneously on shared or overlapping frequencies to provide coverage. WiMAX 2 provides protocols for multi-radio coexistence by allowing the main station to communicate to various base stations via their over the air interface in order to report and schedule operations based on reported co-located coexistence activities [18]. This is to reduce interference and improve efficiency.

e. Multi-hop Relay

An additional method for extending network coverage is the support for multi-hop relay. The network is extended via a series of repeater stations. This provides coverage and enhances data transmission rates in areas of macro-network cell boundaries and gapped coverage areas due to terrain or other interference sources [18].

All of these features make WiMAX 2 an ideal candidate for HAP deployment especially in a tactical or disaster relief environment where users' needs are rapidly changing.

3. IEEE 802.11

The IEEE 802.11 standard is an evolving family of specifications that uses the Ethernet protocol and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [6]. IEEE 802.11, commonly referred to as WiFi, is an ubiquitous technology in the commercial and home marketplace. This is not a candidate for primary data transmission from HAPs, rather it is a complimentary technology to the WiMAX 2 standard to extend the network interface to a vast number of inexpensive user platforms. WiFi typically operates in short range local area applications in the unlicensed 2.4 GHz and 5–6 GHz bands. The integration of WiFi into a HAP based network would be used for short-range hotspot of limited point-to-point applications. The huge advantage of the WiFi standard is its compatibility with commercial off-the-shelf (COTS) equipment. For the end user, it allows for low equipment costs, simple setup, and rapid reconfiguring for ad-hoc environments such as temporary outposts, mobile units, and emergency response. As mentioned previously, the WiMAX 2 standard allows for Multi-RAT integration and handoff allowing a device to seamlessly switch between a WiMAX 2 macro network and a local WiFi hotspot.

C. SMART ANTENNAS

Smart antennas are cooperative or adaptive antenna arrays that are capable of advanced signal processing, spatial beam forming, direction of arrival tracking, and spatial coding. Smart antennas are capable of forming directional radiation patterns, therefore, reducing interference to neighboring beam forms. They also allow for beam steering and tracking [6]. This provides a great deal of flexibility when designing HAP signal coverage areas. It allows for multiple cell formation, steerable spot beams for highly mobile users, and "notching out" of target areas. Notching out is the ability of the antenna to eliminate coverage in a specific area to reduce interference or the potential for signal exploitation. The application of smart antenna technology over traditional fixed aperture antenna designs does present increased technical complexity, but for the tactical application of HAP based wireless data connections, the benefits are numerous. Smart antenna technology allows the system manager to dynamically tailor HAP coverage areas for specific applications while reducing the interception and exploitation of signals in areas where coverage is not needed or desired. This would also allow for more consistent coverage in targeted areas and reduced degradation due to variations in HAP position or attitude. Smart antenna technologies are still evolving and represent an additional layer of complexity because of the additional equipment required to manage the antenna. Figure 9 provides an example of smart antenna application.

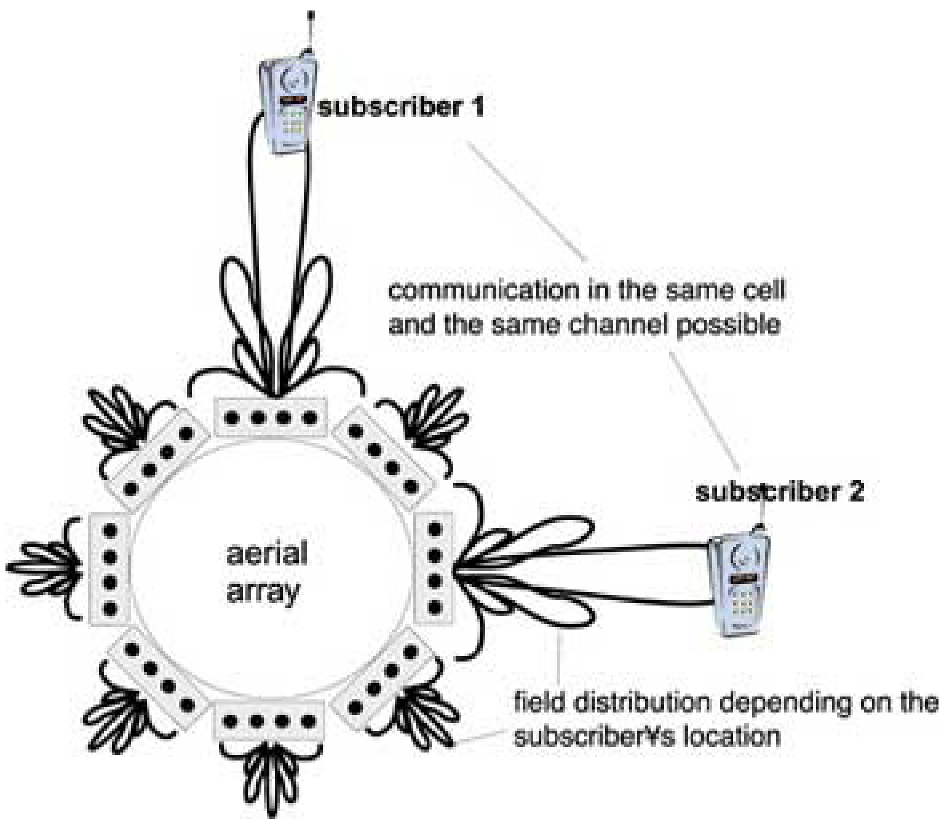

Figure 9. Smart antenna array. From [19].

D. COGNITIVE RADIOS

A cognitive radio (CR) is a transceiver that automatically changes its operating parameters in response to the spectral environment in which it operates. CRs contain a cognitive engine that uses a process known as Dynamic Spectrum Management to monitor the operating spectrum and, in response to operator inputs, can dynamically adjust to the spectral environment, changing frequencies, protocols, waveforms, power and a number of other parameters [6]. CRs operate as an integrated part of a network communications system and continually monitor the environment while communicating that information across the network and to other CRs. The advancing technology of CRs and Smart Antennas may create synergistic effects that allow for advanced network management systems to optimize network performance and reduce interference. The synergy takes place by optimizing performance on the radio frequency (RF) side through the application of smart antennas, and on the transceiver side through the use of CRs to dynamically manage the spectrum for increased network performance and reduced interference with terrestrial networks.

The opportunity arises to fully integrate the Multiple Input Multiple Output (MIMO) functionality of WiMAX 2 with the spectral efficiency of CRs and the transmission efficiency of smart antennas. These technologies could be aggregated into a system that is highly adaptive to its environment, allows for the integration of legacy systems and technologies, and is tailorable to specific applications and tactical needs.

Additionally, the Multi-carrier operational functionality of WiMAX 2 could be enhanced by CRs. As mentioned previously, WiMAX 2 supports carrier channel bonding on both the uplink and downlink signals. That channel bonding can be of differing bandwidths that are either contiguous or non-contiguous.

CRs could be the great enabler of this channel bonding by choosing the optimal channels for the specific operating environment. In a congested RF environment, it may be difficult to find enough unused RF channels to take advantage of WiMAX 2’s full bandwidth. A CR could analyze the RF environment and choose the most efficient frequencies for transmission. As previously stated the frequencies utilized do not need to be contiguous. This allows a CR to achieve maximum bandwidth even in a congested RF environment.

E. NATO FREQUENCY BANDS FOR POSSIBLE HAP USE

In addition to the unlicensed 2 and 5 GHz frequency bands commonly used for military operations, the North Atlantic Treaty Organization (NATO) has other designated frequency bands for use; these include NATO Band III+: 1.35–2.69 GHz and NATO Band IV: 4.4–5 GHz. These two frequency bands are already in use for wireless data transmission and could be used by military HAP systems. A currently fielded tactical broadband wireless system called BRO@DNET™, seen in figure 10, is based upon legacy WiMAX technology, and is currently operating in NATO’s Band IV. It is a terrestrial based network that advertises data rates of 30 Mbits/s over a 50 Km range per hop [20]. In the event of a WiMAX 2 deployment, previously fielded legacy WiMAX equipment would not have to be immediately replaced because the next generation standard is backwards compatible.

Figure 10. BRO@DNET: Battle-proven broadband wireless communication infrastructure solution. From [20].

F. END USER EQUIPMENT

End user equipment refers to the actual equipment the end user uses to interface with the network. They include, but are not limited to, modern smart phones, tactical radios, tablet computers, WiMAX hotspots, and vehicle mounted mobile base stations or repeater stations. This section discusses the compact and lightweight network interface devices that could best serve highly mobile users.

The commercial marketplace is replete with high tech compact devices designed to interface with the legacy LTE and WiMAX standards. Commercial mobile phones operating with LTE and WiMAX are widespread. As mentioned previously, LTE is the preferred technology among mobile telecommunications providers paving the way for the adoption of LTE-Advanced in these markets. Typically, these devices, although extremely affordable, are not all suitable for military use because of a lack of testing, ruggedization or security concerns. This has not stopped their use though. Aviation crews are deploying with tablet computers and e-reader devices to reduce paper clutter in the cockpit.

1. Lockheed Martin's MONAX™

One company that is trying to bridge the gap between commercial devices and military requirements is Lockheed Martin. Lockheed Martin has developed an intriguing product known as MONAX™, seen in Figure 11.

> With MONAX, Lockheed Martin places persistent broadband communications at the fingertips of soldiers anytime, anywhere.
>
> An enhanced version of commercial 3G wireless operating on non-traditional frequencies, the system consists of a unique portable MONAX Lynx sleeve that connects touch-screen COTS smartphones to the MONAX XG Base Station infrastructure on ground or airborne platforms, offering uninterrupted service to soldiers in the field.
>
> MONAX uses a secure RF link, protected through strong, exportable military-grade encryption enabling the transfer of pertinent and sensitive information with speed and ease. With improved range and connectivity while delivering superior link performance in voice, video and data transmission, MONAX ensures that the information soldiers need is only a click away. [21]

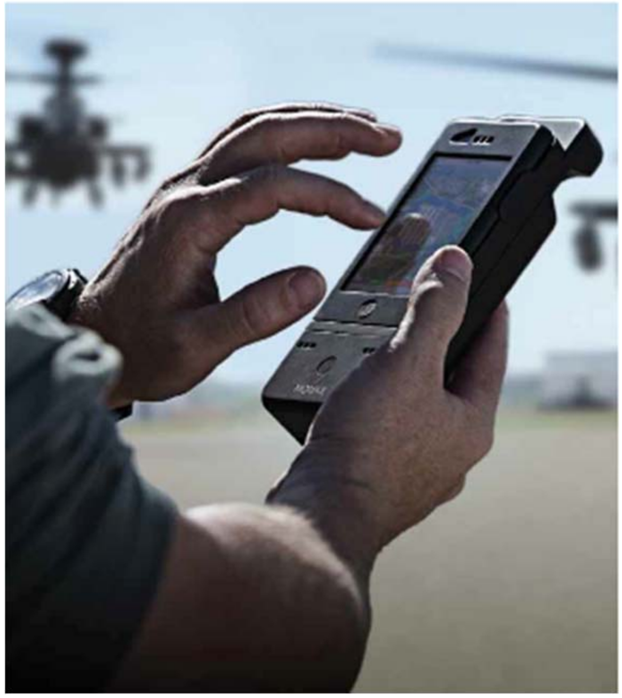

Figure 11. MONAX™ Lynx sleeve with COTs touch screen smartphone. From [21].

MONAX™ is currently based upon Apple Inc.'s iPhone™ smartphone platform with a suite of custom iPhone™ Operating System (iOS) applications specifically written for military use. Lockheed Martin claims that the system is in the process of an upgrade to LTE. Additionally, the MONAX™ XG has been integrated with a tethered aerostat system. In testing and demonstration, a coverage area of 3800 square kilometers was created by a single aerostat mounted base station [22].

2. Smartphone Handsets, Home Base Stations and Hotspots

The information in this section is provided to show the availability of commercial equipment that could be militarized for HAP based network deployment. The mobile handset marketplace is flooded with devices advertising 4G capabilities even though manufactures are only now gearing up for the commercial deployment of the next generation of technology. Several commercial providers, most notably Clearwire Corporation, are offering 802.16e WiMAX service and handsets (see figure 12) in limited markets. Clearwire has partnered with Sprint to provide WiMAX data coverage to their cellular communications network [23].

Figure 12. Sprint WiMAX handset. From [24].

Clearwire also markets WiMAX service as a standalone service provider to residential and commercial customers using WiMAX routers, hotspot pucks and USB dongles (see figure 13) [25].

Figure 13. Clearwire WiMAX products. From [25].

3. Commercial WiMAX Equipment

Due to the lack of commercially available HAPS, equipment specifically designed to support HAP based networks has yet to be developed. More ruggedized commercial WiMAX equipment that is currently available includes Redline Communications products (see Figure 14). They have a line of ruggedized WiMAX products designed for telecom service providers, local and state governments, the oil and gas industry, and military organizations [26]. The equipment is designed to provide ultra high-capacity, extreme-range, specialized wireless data for point to point (PTP) and point to multi-point (PTMP) applications [26]. The commercially available equipment has been designed entirely for terrestrial applications, but does have potential for adaptation to initial testing and proof of concept experimentation.

Figure 14. Redline Communications RDL-3000 Radio Platform. From [26].

G. SUMMARY

In this chapter, some of the potential wireless technologies that could facilitate tactical broad area wireless networking via HAPs were discussed. The discussion focused upon the IMT-Advanced approved technologies of LTE-Advanced and WiMAX 2. LTE-Advanced has become the technology of choice for the commercial mobile phone industry, but of the two technologies examined, the recently ratified IEEE 802.16m WiMAX 2 standard presents the best-suited wireless data solution for a HAP based deployment. To complement the data transmission standard, an overview of some recent radio and antenna technology advances such as cognitive radios, and smart antenna design were examined. These innovations could be implemented into a HAP based network to enhance the level of connectivity required for military applications.

In addition, some of the frequency band and regulatory issues surrounding the development of a HAP based network as well as examples of currently deployed similar technologies and end user equipment were presented in order to give the reader an idea of what currently exists in the commercial marketplace. These COTs products may not currently be suitable for military application, but they show the potential for the integration of the technology into military grade equipment, and the potential for integration of COTs technology for testing and evaluation.

Due to the potential long lead-time in the fielding of suitable HAP platforms for military application, wireless data transmission technologies must be continuously reviewed to determine whether future emerging technologies show better potential for application over existing technologies. Table 1 lists a summary of reviewed technologies.

	IEEE 802.16m WiMAX 2	LTE-Advanced
State of development	Recently approved with testing and hardware development ongoing.	Currently deployed in numerous commercial mobile telecommunications applications.
Potential for HAP Application	Very Good-strongly favored by HAP researchers.	Good-application is favored for commercial service delivery via HAP
Current applications	Still in the testing and development phase. Is favored in developing areas because of lower cost of deployment.	Widely deployed and favored by commercial providers in developed areas.
Suitable range for HAP application	Very Good- WiMAX has the best potential for providing ranges required for HAP application.	Good-designed for shorter-range traditional terrestrial cell networks.
Mesh enabled	Yes-WiMAX 2 was designed to be Mesh enabled with support for multi-hop relay, self-organization and mobile nodes.	No-Research is ongoing to make LTE Mesh enabled but it is not currently part of the standard.

Table 1. Summary of reviewed technologies.

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IV. HAP NETWORK DESIGN

Designing a HAP based network requires a thorough examination of the goals, requirements, and services to be provided. Costs associated with the implementation, benefits over alternative network designs, and the network operating environment also need evaluation. The basic hypothesis of this chapter is that HAP based networks could provide an efficient, cost effective solution to the data transmission requirements of our modern military operations. This chapter proposes and then compares a HAP based solution against traditional terrestrial and satellite based network designs. A great deal of research is ongoing in the fields of space based and terrestrial based networking. The intent of this research is not to replace those networks. Instead, the intent is to demonstrate how a HAP based infrastructure could facilitate expanded coverage and capabilities for reasonable costs while symbiotically integrating with terrestrial and space based platforms.

Included in this chapter is a discussion about the operating environment and how it would affect decisions about frequency allocation, station altitude, and planned coverage area. These are some of the many factors that have to be considered when planning a HAP based network.

A. SPACE BASED NETWORKING

Traditional satellite based military and commercial networking is designed on old technology. The satellite acts as a microwave relay station in space. This requires the satellite to have connectivity to a ground-based relay station in order to interact with the terrestrial based network. So far, none of the Internet Protocol (IP) routing for digital communications happens onboard the satellite: that takes place back on earth. The satellite merely acts as a long-range relay eliminating the need for a wired connection. While this works well, it requires a substantial ground based logistical footprint to support the satellite. There are developments and research in the field of internet routing in space (IRIS).

CISCO and the Department of Defense have teamed up to investigate IRIS. On November 23, 2009, the *Intelsat 14* communications satellite launched into geosynchronous orbit, 22,300 miles above the Earth. Onboard the satellite is an experimental CISCO router designed to test the application of IRIS. The idea is to provide satellites the capacity to communicate with each other and route IP traffic in the same ways that it is routed on terrestrial networks. The test was deemed very successful and shows potential for transforming the satellite communications industry [27]. If IRIS continues to progress in development, it would not solve all of the problems associated with military communications; instead, it would increase space based systems' flexibility by providing more back-haul capacity and enhanced capabilities (e.g., improved throughput, reduced latency). This would allow for greater global connectivity and throughput from military headquarters based in the United States to remote satellite access stations. Given the long lead-time and high cost required for satellite development and launch, this solution's main challenge is funding and the time required to deliver and replace satellites in orbit.

Current military requirements for satellite communications are outpacing the DoD's capacity; therefore, the DoD has turned to commercial providers to fill that gap. This comes at a heavy cost. A recent Air War College research paper gives the example of a DoD user operating a fleet of 40 Iridium satellite phones an average of 3 hours a day. At a cost of three dollars a minute, the airtime bill alone would be nearly 8 million dollars for the year [28]. This example is just a fraction of the hundreds of millions of dollars the DoD spends on leased commercial satellite service every year.

B. HAP VS. TERRESTRIAL VS. SATELLITE INFRASTRUCTURES

Many comparisons can be made between HAP, terrestrial, and satellite infrastructure designs. It is recognized that much of the research in the commercial marketplace does not consider factors pertinent to military operations. Viewing through a military lens, this thesis focuses on system growth capacity, geographical coverage, and the cost and size of mobile user terminal equipment and ground infrastructure requirements [29]. A military solution must be scalable, agile, reliable, affordable, defendable, rapidly deployable, and require minimum in theatre ground infrastructure.

This section briefly expands each of the infrastructure issues while keeping in mind the pertinent military consideration factors. The cost and size of mobile user terminal equipment is a very pertinent issue. A HAP based wireless data network would be structured similarly to the ubiquitous commercial mobile phone networks: the handset/mobile terminal technology is well developed, small, and inexpensive. Satellite equipment is more specialized, larger, and more costly than terrestrial network equipment. The size and power requirements make it less desirable for military application. The terminal equipment needed to access a HAP network is nearly identical to the equipment required to access terrestrial networks. The technologies used are not as wide spread, but the size and cost are comparable to commercial mobile phone and data equipment [29].

Figure 15 shows a comparison of HAP, satellite and terrestrial propagation environments [6]. It is intended to give the reader a frame of reference for understanding the different environments in which satellites, HAPs, and terrestrial towers operate. The concepts displayed in the figure are examined in this section.

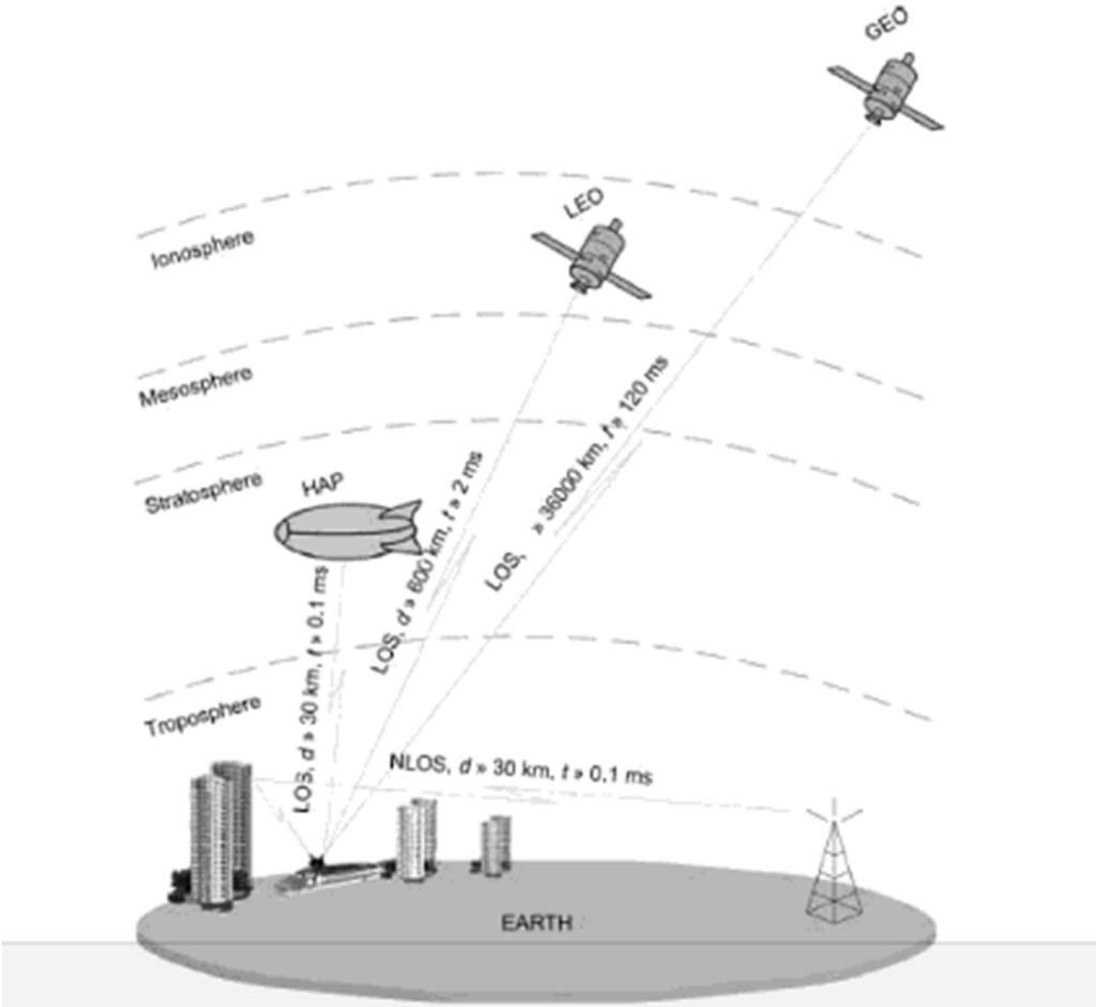

Figure 15. Comparison of HAP, satellite and terrestrial propagation environments. From [6].

1. Growth Capacity and Scalability

System growth capacity is an important factor. Terrestrial networks require the deployment of a large amount of equipment into the area of desired coverage. From a military perspective, terrestrial networks require large amounts of indefensible infrastructure (i.e., equipment, towers, and power generation stations). Even in the commercial world, the build out of a mobile phone network takes years, making it useless for expeditionary military application.

Satellite based networks are limited to their existing capacity because the growth of additional capacity is limited by the cost and availability of new satellites and launch systems to put them in orbit [29]. With the associated massive costs, limited launch availability and long lead times, adding satellite network capacity is not affordable or rapidly deployable. For rapid military response to crisis or disaster events, satellite availability is rather fixed. Limited scalability exists through the integration of commercial systems, but those services are rather fixed in capacity as well. In theory, rapid HAP network deployment and capacity expansion is achievable. With an affordable investment in some key infrastructure equipment, setting up a HAP based network anywhere in the world would only take days to achieve [30]. From the military perspective, this has great potential for both conflict related communication needs and HADR scenarios that are both primary missions that the U.S. military is mandated to support.

In addition to being flexible and rapidly deployable, the HAP based network would be reliable and require minimal and possibly no in-theatre ground infrastructure prior to deployment. This is a significant consideration. A HAP based network could be rapidly deployed and scaled up or down based upon demand and size of the area of operations. Expeditionary forces are always limited in terms infrastructure, the amount of equipment they can carry and their maintenance and power requirements. A system that would minimize and potentially reduce the weight and size of equipment an expeditionary force has to carry into theater, while providing enhanced connectivity, would be immensely beneficial to military forces. Table 2 lists an example of several platform types as well as their associated mission durations, data capacities, costs, response times and availability.

Platform	Mission Duration	Altitude km	Data Capacity	Cost **$M**	Time to Deploy	When Available
Highly Tactical “Unteathered Balloon or UAV”	< 1 day	4 +	2 Mbps	.15	Minutes	Now
Tactical	2 days to 2 weeks	15	50 Mbps	.75	Hours	Soon
Moderately Strategic “HALE-D”	2 – 4 Months	21	1 Gbps	3	1 day	2 years
Strategic “HAA”	> 6 months	21	10 Gbps	15 +	2 days	5 years

Table 2. Ariel platform hierarchy. After [30].

2. Coverage

Geographic coverage of the network depends on a few factors. Most notably are antenna height, power and terrain. Terrestrial networks are range limited to only a few kilometers around each base station because of antenna height, rapid signal attenuation and terrain masking (e.g., shadow zones caused by hills, valleys, and man-made structures). Satellite networks can cover the entire earth’s surface, but require multiple satellites to do it. A low earth orbit (LEO) satellite constellation consists of 20 to 40 satellites at an altitude 500 to 1500 km. A medium earth orbit (MEO) network usually consists of 8 to 20 satellites at an altitude of 5000 to 12000 km. While a single geostationary satellite (GEO) at approximately 36000 km can cover 34% of the surface of the earth and can achieve near total coverage with only 3 satellites. The clear benefit of a satellite-based network comes from its height above the earth, hence their larger geographic coverage area and relative safety from attack by all but the most technologically advanced nations; however, as discussed earlier, the advantage comes with great costs and many restrictions [29]. HAPs fall in between terrestrial towers and satellites in regard to geographic coverage. A single HAP at an altitude of 20 to 25 km can provide a coverage area with a diameter of 300 km. This is the equivalent to the island nation of Haiti covered by a single airship. Far greater coverage areas are achievable in a multi-HAP architecture [30].

3. Cost Factor

Cost is always a factor in architecture design considerations. The three types of infrastructures are all costly and represent a significant capital investment for a corporation, nation, or military. The leader in terms of infrastructure cost is the satellite-based architecture. The costs of building and expanding satellite networks are often measured in the billions of dollars. Clearly making expanded satellite networks the most expensive upfront investment. Specific costs for a HAP base network are unknown, but estimates place costs on par or less than the costs associated with the deployment of a terrestrial system [29]. HAPs show significant possibilities of providing satellite like coverage at significant cost savings over the build out or expansion of additional satellite networks.

The comparisons between HAP based networks and terrestrial communications networks are drawn from research done in providing commercial services to industrialized areas. They do not take into account the issues that must be addressed in military scenarios such as deployability and defensibility. This is why large-scale terrestrial networks have never been a military option, and why modern military operations have relied so heavily on satellite connectivity. Table 3 lists some additional network characteristics for consideration when comparing the three systems.

Issue	Terrestrial wireless	Satellite	High Altitude Platform
Availability and cost of mobile terminals	Huge cellular/PCS market drives high volumes resulting in small, low-cost, low-power units	Specialized, more stringent requirements lead to expensive bulky terminals with short battery life	Terrestrial terminals applicable
Propagation delay	Low	Causes noticeable impairment in voice communications in GEO (and MEO to some extent)	Low
Health concerns with radio emissions from handsets	Low-power handsets minimize concerns	High-power handsets due to large path losses (possibly alleviated by careful antenna design)	Power levels like in terrestrial systems (except for large coverage areas)
Communications technology risk	Mature technology and well-established industry	Considerably new technology for LEOs and MEOs; GEOs still lag behind cellular/PCS in volume, cost and performance	Terrestrial wireless technology, supplemented with spot-beam antennas; if widely deployed, opportunities for specialized equipment (scanning beams to follow traffic)
Deployment timing	Deployment can be staged, substantial initial build-out to provide sufficient coverage for commercial service	Service cannot start before the entire system is deployed	One platform and ground support typically enough for initial commercial service
System growth	Cell-splitting to add capacity, requiring system reengineering; easy equipment upgrade/repair	System capacity increased only by adding satellites; hardware upgrade only with replacement of satellites	Capacity increase through spot-beam resizing, and additional platforms; equipment upgrades relatively easy
System complexity due to motion of components	Only user terminals are mobile	Motion of LEOs and MEOs is a major source of complexity, especially when intersatellite links are used	Motion low to moderate (stability characteristics to be proven)
Operational complexity and cost	Well-understood	High for GEOs, and especially LEOs due to continual launches to replace old or failed satellites	Some proposals require frequent landings of platforms (to refuel or to rest pilots)
Radio channel "quality"	Rayleigh fading limits distance and data rate, path loss up to 50 dB/decade; good signal quality through proper antenna placement	Free-space-like channel with Ricean fading; path loss roughly 20 dB/decade; GEO distance limits spectrum efficiency	Free-space-like channel at distances comparable to terrestrial
Indoor coverage	Substantial coverage achieved	Generally not available (high-power signals in Iridium to trigger ringing only for incoming calls)	Substantial coverage possible
Breadth of geographical coverage	A few kilometres per base station	Large regions in GEO (up to the 34% of the earth surface); global for LEO and MEO	Hundreds of kilometers per platform (up to 200km)
Cell diameter	0.1–1 km	50km in the case of LEOs. More than 400km for GEOs	1–10 km
Shadowing from terrain	Causes gaps in coverage; requires additional equipment	Problem only at low elevation angles	Similar to satellite
Communications and power infra-structure; real estate	Numerous base stations to be sited, powered, and linked by cables or microwaves	Single gateway collects traffic from a large area	Comparable to satellite
Esthetic issues and health concerns with towers and antennas	Many sites required for coverage and capacity; "smart" antennas might make them more visible; continued public debates expected	Earth stations located away from populated areas	Similar to satellite
Public safety concern about flying objects	Not an issue	Occasional concern about space junk falling to Earth	Large craft floating or flying overhead can raise significant objections
Cost	Varies	More then $200 million for a GEO system. Some billion for a LEO system (e.g., $5 billion for Iridium, $9 billion for Teledesic)	Unspecified (probably more than $50 million), but less than the cost required to deploy a terrestrial network with many base stations

Table 3. Basic characteristics of terrestrial wireless, satellite, and HAP systems. From [29].

C. POTENTIAL NETWORK DESIGNS

Designing a network architecture that incorporates HAPs leverages many of the principles used today in both terrestrial and satellite networks. A HAP could be viewed as a low geostationary satellite or a very tall terrestrial tower. One of the limitations that geosynchronous satellites have is that they can only be placed over the equator. A HAP with its onboard propulsion and navigation systems would have the ability to remain fixed over a specific point on the earth's surface. This brings together the advantages of fixed position like a tower and the coverage like a satellite. From a military perspective the system architecture must be open and adaptable to the needs of the operation as well as the resources available. Multiple system architectures are possible to employ.

1. Single HAP with Off-board Routing

The simplistic model shown in Figure 16 uses a HAP as a base transceiver to extend the reach of a network [31]. No IP routing takes place onboard the HAP; that takes place at a ground station as part of the terrestrial network connecting to the HAP. This is similar to the way current satellite communications operate. This off-board routing still maintains a significant advantage over satellite based networks when accounting for the limited bandwidth and latency issues that plague satellite communications. The concept of latency can quickly be explained as the delay in time that it takes for the radio signal to travel to its destination. In satellite communications, this is a significant factor. A satellite in LEO orbit will experience signal latency of 2 ms and a GEO based satellite experiences signal latency on the average of 120 ms [6]. The listed times account for only one-way propagation; the total latency for the round trip is double plus any onboard repeater delay. The latency for HAP based signal propagation is nearly the same as one-way terrestrial links at about 0.1 ms [6].

This simple model has utility in specific situations, but lacks the ability to scale up and take advantage of additional technology. It would rely exclusively on its backhaul link capacity for off-board routing, thus increasing delays in data transmission. A simple scenario of a voice transmission from one handset to another located nearby would require the signal to travel to the HAP, and then be repeated to the base station for routing. The transmission would need to make the return trip from the routing base station back through the HAP and down to the destination handset. Although faster than the same scenario involving satellite telephones, there is still inefficiency in the design.

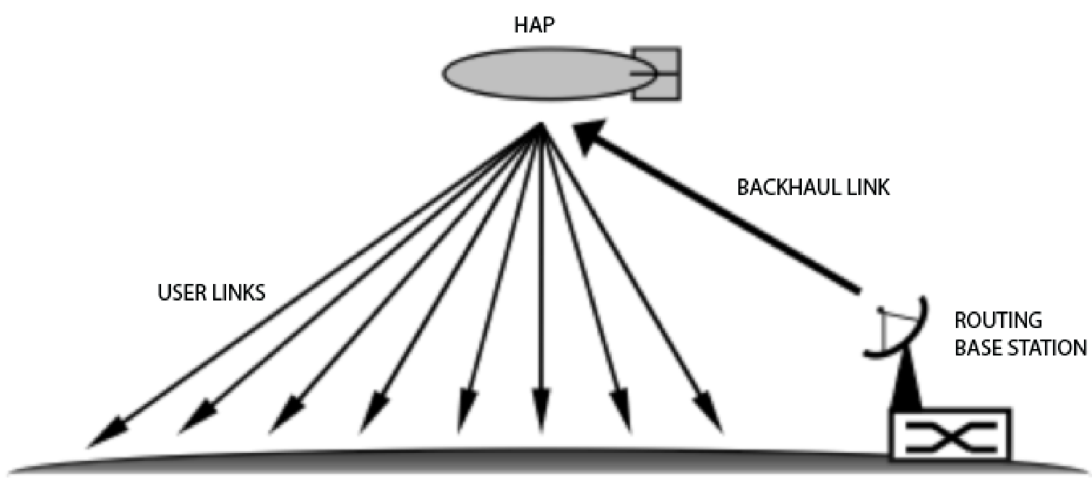

Figure 16. HAP working as a base transceiver station. From [31].

2. Single HAP with On-board Routing

A more advanced model provides the HAP with its own onboard routing capability. Shown in Figure 17, this reduces the HAP's dependence on backhaul connections and allows the network to operate more efficiently by reducing latency and allowing the onboard router to prioritize traffic. This is especially true for point-to-point data or voice connections using the same HAP wireless link. By routing intra-HAP traffic onboard the HAP, the backhaul link is not required and the degree of separation between the users is reduced to one. While not truly a peer-to-peer connection, it would be very efficient for both voice and data communications.

The ability to perform onboard routing also opens the door to the concept of “cognitive routing.” The concept of “cognitive routing” is continuing to develop. Initially cognitive routing focused on physical layer routing in dynamic or ad-hoc network environments. The intent was to create intelligent routing algorithms that could balance network loads and be self-healing in dynamic networks. The author suggests that this concept needs to be expanded to include content-based routing into the cognitive model [32]. By including content prioritizations into the routing algorithms the HAP router could prioritize network traffic based on defined criteria to guarantee quality of service (QOS) levels to designated services, applications or data types.

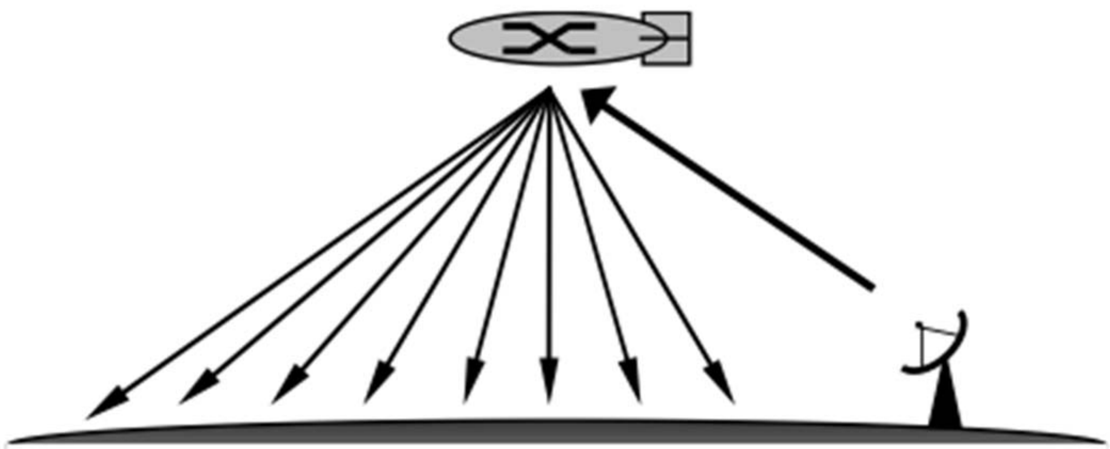

Figure 17. HAP working as an independent system. From [31].

The on-board routing concept still requires a backhaul link to distribute data into the larger network, but it would improve overall performance. The previously used example of a voice transmission from one handset to another can be used here to understand the advantage. A radio operator making a voice transmission to another station through a traditional line of sight radio could be masked by terrain or buildings, but if they were within the coverage umbrella of a HAP, communications would be possible. The transmission would travel up to the HAP. Its onboard routing equipment would determine the most efficient path to the destination along with the priority of the data and bandwidth required. It would then send that transmission back down to the destination handset without the need to forward the transmission to a base station for routing. The router could also apply a logic scheme that prioritizes network traffic based upon content (e.g., giving higher priority to voice transmissions to insure unbroken reception). This would reduce transmission delays and free up backhaul bandwidth for additional tasks such as streaming surveillance video back to a headquarters for analysis.

3. Multi-HAP Network with On-board Routing

Figure 18 displays the most flexible and robust architecture model. It is a multiple-HAP network using Inter-Platform links to connect HAPs and multiple backhaul links. This type of architecture, with the ability to scale it up and down, provides great utility to the military. Figure 18 depicts a large operations area with significant barriers to communication (e.g., mountains, oceans, and cities), robust users (e.g., ships, foot and mounted soldiers, and a variety of airborne platforms), and multiple links.

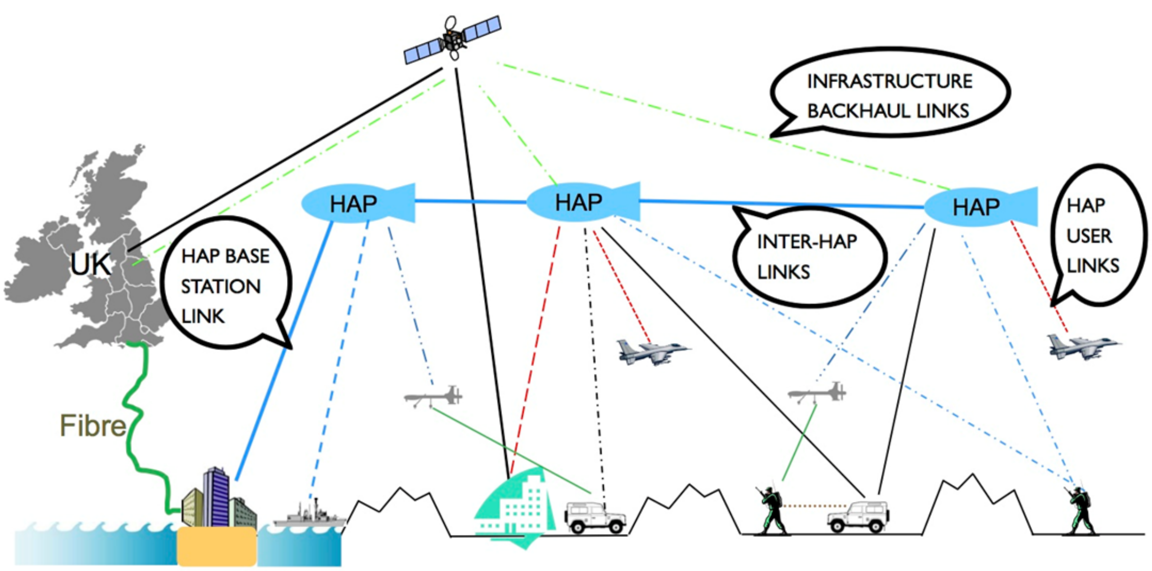

Figure 18. Multi-HAP system architecture. After [30].

Providing high-speed wireless data and voice connectivity to the battlefield or disaster areas requires a great deal of connectivity. A HAP based network should not be viewed as a replacement solution for satellite or terrestrial networks, but instead as a facilitator between the two. As displayed in Figure 18, the Multi-HAP constellation would continue to rely upon satellite connections for backhaul to the larger network, but could also utilize alternative paths for data. Ideally, the three systems would function together symbiotically. A HAP based constellation could reduce the need for expanded satellite infrastructure by acting as an intermediary. The improved link quality available to the HAP for satellite backhaul would improve the efficiency of existing satellite infrastructures. Additionally, in situations where the HAP network would have access to both satellite and terrestrial backhaul links, as displayed in Figure 18, the overall capacity of the network could be increased by cognitive routing schemes that would determine which backhaul link to use to provide the shortest and most efficient path to the destination, as well as the priority of the data.

a. Mesh Enabled Network

The description of a multi-HAP network above utilizes a concept known as Mesh networking. Mesh networking is an evolving technology and includes concepts such as self-forming and self-healing networks. A multi-HAP based network should be mesh enabled to take full advantage of its flexibility and adaptability. Examining the depiction of a multi-HAP network in Figure 18, one can see the benefit of a self-organizing mesh network. By being mesh enabled a multi-HAP network would be able to adapt to changing network demands and coverage requirements. HAP nodes could be added, removed or repositioned dynamically to adjust to the users' demands. For example, a HAP node could be repositioned or added to expand coverage to a previously uncovered area in support of ground troop movements.

The advantages of mesh networking also apply to lower level nodes such as the UAVs depicted in Figure 18. By being a mesh network, dynamic changes are supported in the upper level nodes (i.e., HAP), intermediate nodes (e.g., UAVs and manned aircraft), and also the *supported* ground nodes (e.g., headquarters and troops on the move). In this type of mesh network, nodes are capable of joining and leaving the network without significant network administration and configuration issues. Hence, the ideas of self-forming and self-healing provides that flexibility. This is an advantage of the WiMAX 2 technology discussed in chapter three. It was designed with Mesh networking in mind and is fully supported in the protocol.

A great deal of work has been done in the fields of mobile ad-hoc networks (MANET) and mesh networking. The concept of HAP utilization is not to diminish the need for MANET technologies; rather it is to work in concert with them. By applying a layered systems principle to the network design, we can see an organized structure emerge. The structure would appear as layers of networks that interact and support each other. The HAP based mesh network would be aware of the underlying smaller MANET nets and vice versa. The satellite and terrestrial networks that the HAP network would interact with would appear as additional system layers.

b. HAP Backhaul Links and Payload Planning

Much of this thesis has focused on networking technologies to link the HAP to the end-user, but in a complex multi-HAP environment, there is more going on than just HAP to end-user links. A significant requirement is the infrastructure links, or what is commonly referred to in the telecommunications field as backhaul links. In any HAP deployment scenario, whether single or multiple, backhaul capabilities are required. The backhaul links connect the HAP to the ground infrastructure, space infrastructure and for multi-HAP deployments the inter-HAP network. In the satellite industry, there are various techniques and technologies available for these links. All network designs have to take into account the various needed backhaul links depending upon the application of the network and plan the HAP payloads accordingly. This is to ensure that the technology required for accessing the different types of backhaul connections is onboard the HP. A HAP based network is reconfigurable while active through relief on station: a HAP is replaced by a new HAP with an updated payload. The operating HAP would hand over network responsibilities to the oncoming HAP, and then return to earth for servicing, upgrading, and redeployment. This is impractical with a satellite.

D. OPERATING ENVIRONMENT

The design of a HAP based network must take into consideration some of the environmental factors that affect HAP placement, equipment requirements, and RF propagation. This section discusses RF propagation and some of the physical characteristics and atmospheric effects that influence network design and performance.

1. Operating Altitude

As previously discussed, a HAP could be viewed similarly to a geostationary satellite. This is true with a few exceptions. Geostationary satellites are limited to a position above the earth's equator. This does affect their coverage over the high latitudes (i.e., near the earth's poles) due to the curvature of the earth. A HAP would not have this limitation; it could be deployed to any spot above the earth's surface and have the ability to maintain that station.

The literature published on HAP design suggests the optimal station altitude for a HAP deployment ranges from 20–25 Km [6]. That altitude is primarily based on typical stratospheric wind profiles that are favorable to LTA platforms. A major consideration in choosing this altitude block is the requirement that HAPs maintain station over a specific point on the earth. They will require enough motive capacity (i.e., thrust and navigation) to transit to their desired station location and then maintain that station and provide continuous network coverage to the desired area. Maintaining station and long endurance is facilitated by the light winds. The average wind speed in the 20–25 Km altitude zone is 5–10 m/s [29]. Lower winds mean HAPs would need less power to maintain station; therefore, its energy could be conserved for other mission functions (e.g., powering onboard communications equipment, and re-tasking).

Figure 19 displays the average atmospheric wind speed with respect to altitude and shows why the altitude block described is so favorable.

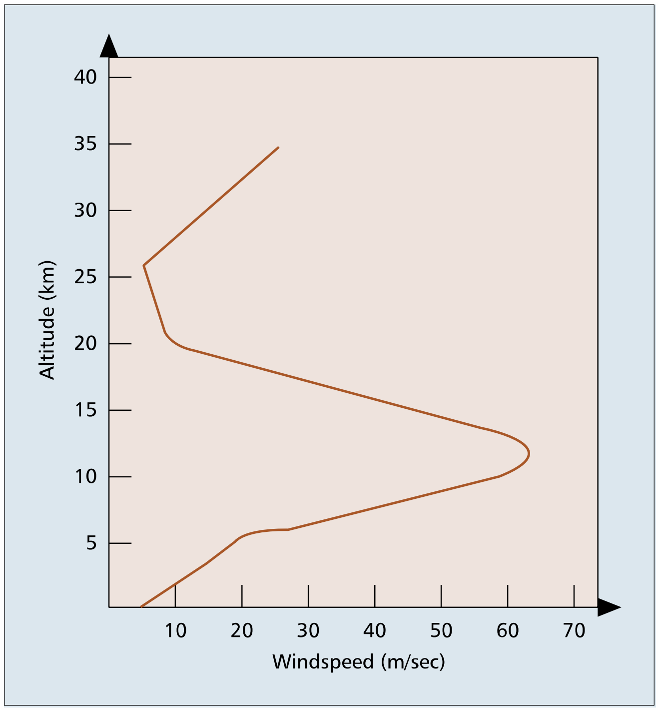

Figure 19. Wind speed vs. altitude. From [29].

Conveniently, that altitude block nearly matches the 60,000 ft ceiling for controlled commercial air space putting the desired HAP station block above commercial and most military air traffic. To put the units into perspective, 20 km equates to 65,616 ft—well above all commercial air traffic. The International Civil Aviation Organization (ICAO) limits class A or controlled airspace to Flight Level 600, approximately 60,000 ft. Some countries do recognize controlled airspace up to Flight Level 660, approximately 66,000 ft, but current airliners rarely fly above 41,000 ft because of pressurization limitations. This means that the optimal altitudes for HAP deployment are safely above nearly all air traffic.

2. Atmospheric Effects

The atmosphere that a radio signal passes through affects it in several ways. Atmospheric effects such as free space loss, absorption due to atmospheric gasses, scintillation, and moisture effects are discussed in detail. These atmospheric effects are pertinent to the design of the network when choosing operating frequencies. The thesis will use this discussion to address where the optimal slots in the frequency spectrum reside for HAP employment.

a. Free Space Loss

Free space loss of a radio signal is the spreading out of the signal energy over distance. Frequency does play a part in the loss, but the biggest factor in determining free space loss is distance from the source. Although this is combated with antenna design and beam forming techniques, it cannot be completely overcome. Figure 20 plots the free space path loss for relevant HAP operating frequencies as a function of elevation angle. The elevation angle equates to distance, the lower the elevation angle the further the signal has to travel.

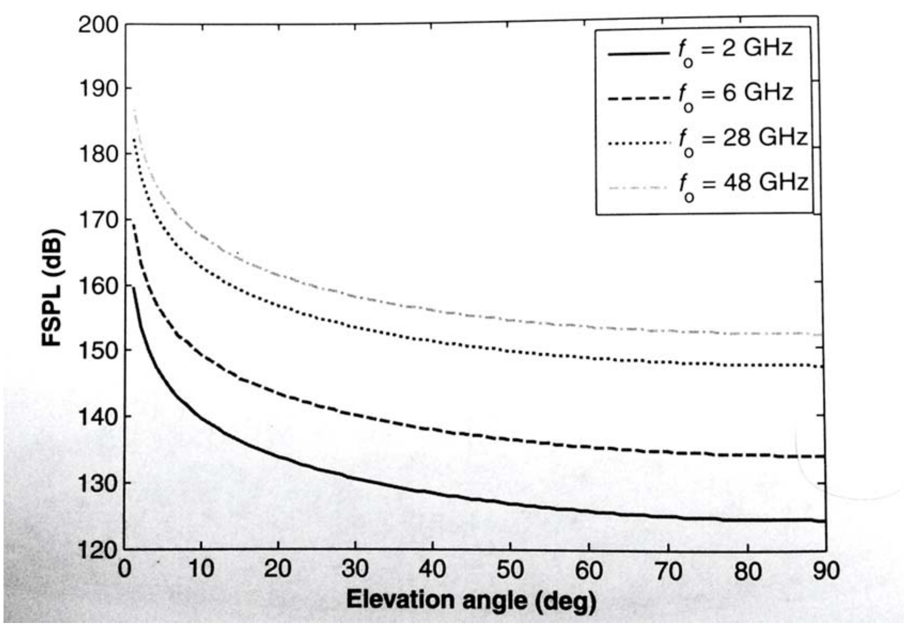

Figure 20. The free space path loss as a function of elevation angle. From [6].

b. Absorption Due to Atmospheric Gases

Frequency absorption due to atmospheric gasses is more of a factor for frequencies above 10 Ghz. It is also a function of distance. Figure 21 shows the loss again as a function of the elevation angle. As displayed in the figure, frequencies above 10 Ghz experience a much higher level of attenuation.

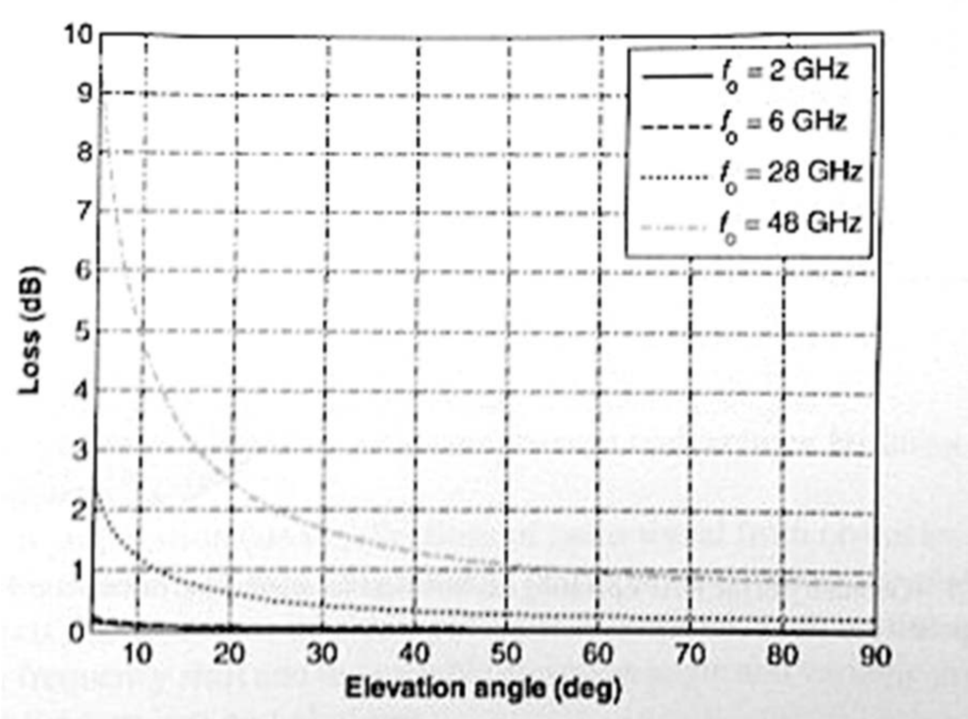

Figure 21. Attenuation due to atmospheric gases. From [6].

c. Scintillation

Scintillation is rapid variations in the received signal due to turbulence in the atmosphere. When air masses of various temperatures, pressures and humidity mix, it causes random variations in the refractive index causing fluctuations in signal direction of arrival and amplitude. This too is affected by elevation angle. The lower the elevation angle the longer the link path through the atmosphere and the higher the scintillation [6]. Figure 22 illustrates the geometry scintillation on HAP signals.

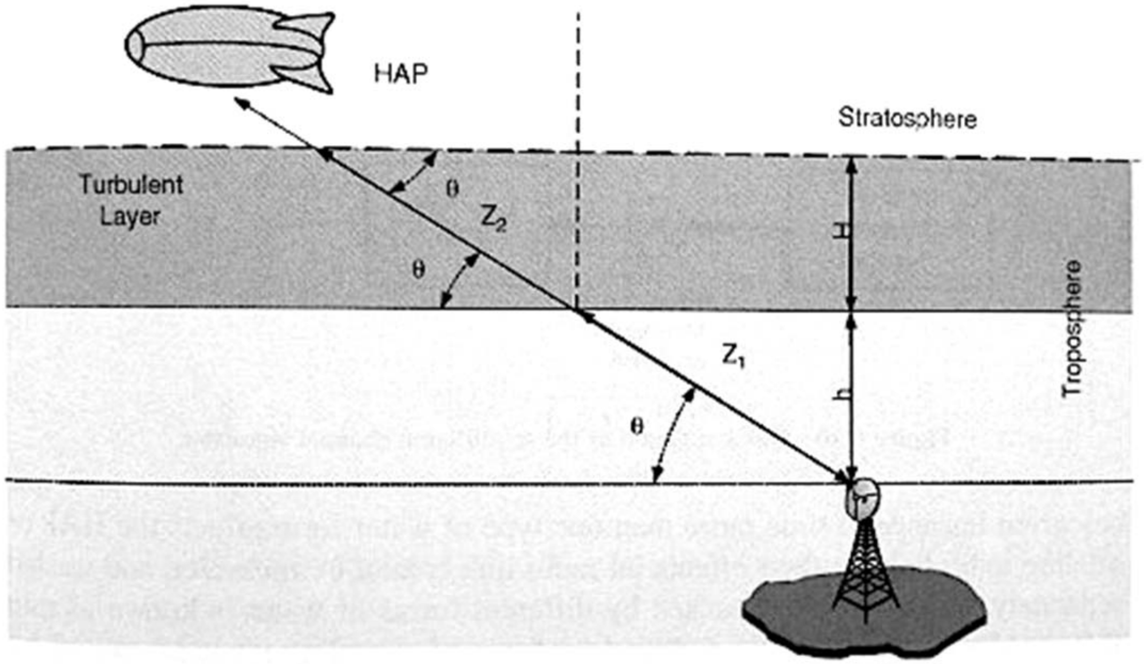

Figure 22. Geometry of the scintillation model for HAP operation. From [6].

d. Moisture Effects

Moisture in the atmosphere can take many forms from vapor and clouds to rain, ice and snow. This atmospheric moisture has an attenuating affect upon RF signals. This is referred to as the rain affect or rain fade. Based on the graph in Figure 23, rain fade starts to become an issue for frequencies above 7 Ghz although it is often considered negligible for frequencies below 10 Ghz. This is important to note when deciding upon HAP transmission frequencies.

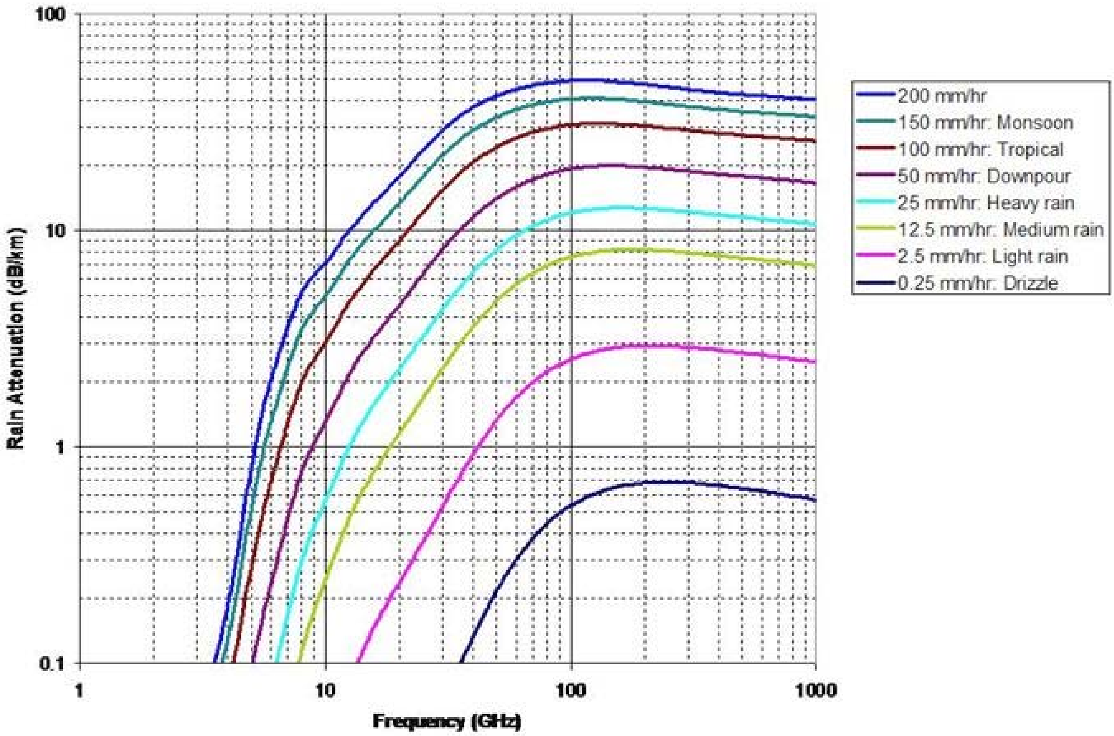

Figure 23. Rain attenuation in relation to frequency. From [33].

e. Optimal Frequency Allocation

Based upon a brief review of some atmospheric effects upon RF propagation and attenuation, the conclusion is that at least for the HAP to end-user links the frequency band from 2–10 Ghz offers the best performance considering the aforementioned atmospheric effects.

3. Coverage Area

In line with the above information regarding atmospheric effects and the effects of elevation angle upon signal attenuation, the topic of coverage area is addressed. As mentioned previously, a single HAP could provide a coverage area with a diameter of 300 Km. This thesis concludes that this is the maximum coverage area that a HAP could provide while maintaining reliable connectivity. Table 3 shows a simple comparison of signal elevation angle with respect to radius of a HAP coverage area. As displayed in Table 4, a HAP stationed at an elevation of 20 Km has an elevation angle of 7.59 degrees at the outer edge of its coverage area. A HAP stationed at 25 Km has an elevation angle of 9.46 degrees. Thus reducing the atmospheric effects that begin to become more pronounced at elevation angles less than 10 degrees.

HAP Elevation	Radius of HAP Coverage area.					
20 Km	100 Km	110 Km	120 Km	130 Km	140 Km	150 Km
Elevation Angle	11.31	10.30	9.46	8.75	8.13	7.59
25 Km	100 Km	110 Km	120 Km	130 Km	140 Km	150 Km
Elevation Angle	14.04	12.80	11.77	10.89	10.12	9.46

Table 4. Elevation angle with respect of coverage radius and HAP altitude.

The above mentioned atmospheric effects on RF propagation coupled with the data on elevation angle leads to the conclusion that planned HAP coverage areas should be no larger than 300 Km and that the optimal frequency band for end-user applications be between 2–10 Ghz. This is not to say that all HAP based networks should be designed to this maximum range. The smaller the planned diameter of coverage is, the better the level of performance will be.

Most commercial modeling of HAP based networks call for smaller coverage diameters commonly ranging between 100 to 200 Km. This is based primarily based upon the service delivery model they are using. Their service delivery models are based upon providing commercial services to urban areas with high user density. These same factors must be accounted for in planning HAP coverage for military application. Coverage diameter should vary based upon the demand and surface environment. Larger coverage areas could be planned for low density environments such as maritime areas, while smaller footprints should be employed for areas with large troop concentrations and or uneven terrain.

E. SUMMARY

This chapter covered many aspects of HAP network design from requirements, costs, integration with existing networks, RF propagation, and physical network design. HAPs should not be viewed as a replacement for existing infrastructures but as capability enhancer. For most military applications, the thesis concludes that the single HAP with onboard routing or the multi-HAP configuration is ideal. It would provide good flexibility, quality of service, and scalability. From the discussion on RF propagation, it has been shown that the preferred operating band for HAP to end-user links is between 2–10 Ghz, and that a single HAP should be able to provide coverage up to 300 Km. The proposed multi-HAP solution could be just what the military needs to provide the bandwidth and connectivity required during modern combat and humanitarian response operations.

V. HAP BASED MISSIONS AND POTENTIAL APPLICATIONS

Much in this paper has focused on the proposed communications mission for HAPs; however, there are additional tasks that could be supported in conjunction with the communications mission. These tasks include intelligence, surveillance and reconnaissance (ISR), operationally responsive space (ORS), blue force tracking (BFT), and situational awareness (SA). This chapter addresses these tasks and how they could be integrated into HAP based networks.

A. INTELLIGENCE, SURVEILLANCE AND RECONNAISSANCE (ISR)

ISR is a broad term used to encompass a number of missions. ISR tasks are broken down into intelligence gathering, surveillance and reconnaissance. There are many different ways that ISR missions could be incorporated into a HAP's payload package. The following section will touch on how these missions could be aided by or incorporated in the network design.

1. Intelligence

Several intelligence collection disciplines would benefit by the application of HAP capabilities. These disciplines are commonly referred to in military parlance as the "INTs." They are Geospatial Intelligence (GEOINT), Signals Intelligence (SIGINT), Measurement and Signature Intelligence (MASINT), Human Resources Intelligence (HUMINT), and Open-Source Intelligence (OSINT) [34]. The three that could benefit the most from HAP-based system are GEOINT, MASINT, and SIGINT. These will be discussed in more detail individually.

a. GEOINT

> Geospatial intelligence (GEOINT) is defined as exploitation and analysis of imagery and geospatial information to describe, assess, and visually depict physical features and geographically referenced activities on the Earth. Imagery intelligence involves the collection

> of images that are recorded and stored (on film, digitally, on tape, etc.). These images can be used to help identify and locate adversary military forces and facilities and give the commander insight into the adversary's capabilities. GEOINT can also help provide commanders environmental and geospatial information. [34]

GEOINT is most commonly thought of as Imagery Intelligence (IMINT) but it does encompass more than just imagery. It also encompasses environmental and geospatial information. HAPs can serve many roles in the world of GEOINT. Today's commanders and ground forces have become ever more reliant upon imagery and full motion video for intelligence gathering and operations. This is evidenced in the rapid growth and demand for UAVs and manned assets to provide this information. The rapid growth in full motion video (FMV) has created bandwidth concerns as the DoD has become very reliant on commercial satellite service in order to distribute this data. It has also sparked a surge in defense products for the distribution of FMV to the tactical user like ROVER and PACWIND, both of which are line of sight systems. These systems have advanced tremendously and have products for ground forces to receive FMV. An example of the latest generation ROVER 5 handheld is in Figure 24.

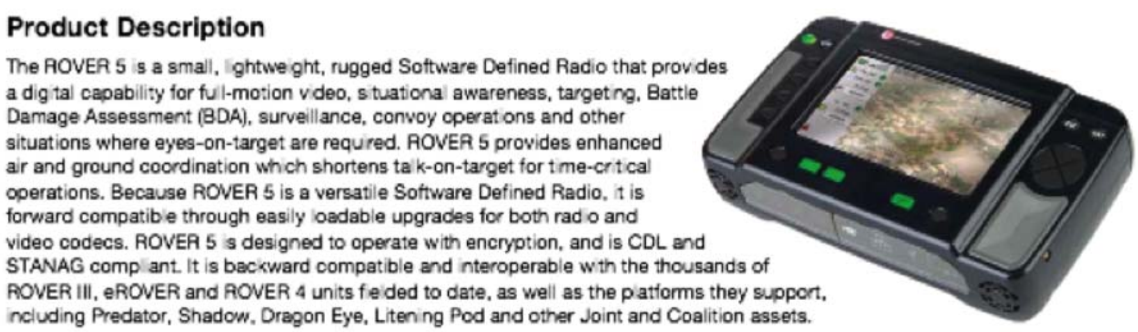

Figure 24. ROVER 5 handheld receiver. From [35].

By covering the battlefield with long-range broadband wireless data, end-users could have access to more video feeds from greater distances on smaller devices without the limitations of current line of sight systems. The major force multiplier that HAPs could provide is merely the dramatic increase in capacity to feed commanders with more data. The HAP could not only serve as a way to transmit more data to end-users, but as a sensor platform itself by loading IMINT payloads onboard the HAP. This would not provide the tactical functionality of our current suite of UAVs but could serve as another eye in the sky. Additionally other non-imaging GEOINT sensors could be deployed on the HAP.

b. SIGINT

> SIGINT is defined in JP 1–02 as a category of intelligence comprising either individually or in combination all communications intelligence (COMINT), ELINT, and foreign instrumentation signals intelligence (FISINT), however transmitted. More specifically, SIGINT uses intercepted electromagnetic emissions to provide information on the capabilities, intentions, form-actions, and locations of adversary forces. COMINT consists of information derived from intercepting, monitoring, and locating the adversary's communications systems. COMINT exploits the adversary's communications, revealing the adversary's intentions. ELINT consists of information derived from intercepting, monitoring, and locating the adversary's non-communication emitters. It exploits the adversary's radar, beacon, and other non-communication signals, allowing friendly forces to locate adversary radars and air defense systems over a wide area. FISINT consists of technical information derived from the intercept of electromagnetic emissions, such as telemetry, associated with the testing and operational deployment of foreign air and space, surface, and subsurface systems. FISINT can provide technical details of foreign weapons system development so U.S. forces can respond quickly to new technological developments. [34]

SIGINT plays a vital part of both national strategic security and tactical level decision-making. In fact, SIGINT and COMINT are increasingly indispensable in modern warfare. HAPs, if properly equipped, could play a vital SIGINT role by providing a platform with extended on station time for intelligence collection. The data network would then allow the more efficient exploitation and transmission of that intelligence. A multi-HAP network could be used to conduct

SIGINT collections over a broad area. It could then forward that data down to intelligence analysts on the ground. This would go a long way toward providing the unblinking eye and ear in the sky.

c. MASINT

> Measurement and signature intelligence (MASINT) is scientific and technical intelligence obtained by quantitative and qualitative analysis of data (metric, angle, spatial, wavelength, time dependence, modulation, plasma, and hydromagnetic) derived from specific technical sensors for the purpose of identifying any distinctive features associated with the target. The detected feature may be either reflected or emitted. Examples of MASINT might include distinctive infrared signatures, electronic signals, or unique sound characteristics. MASINT can be collected by ground, airborne, sea, and space-based systems. MASINT can be used to monitor potential adversary technical developments and deployments, as well as emerging weapons of mass destruction (WMD) threats. While MASINT is often used in scientific and technical intelligence (S&TI) products, it is becoming increasingly important in the operational area. [34]

Instrumentation for the collection of MASINT is another intelligence gathering activity that can be supported via HAPs. An important design principle that could facilitate these collection activities would be payload modularization. Through payload modularization, the HAPs onboard equipment could be individually tailored for the desired mission.

B. OPERATIONALLY RESPONSIVE SPACE

In 2007, the Operationally Responsive Space (ORS) Office was formed to take a proactive approach at developing flexible and timely solutions for our space needs. “The ORS Office is implementing a rapid innovation process using a Modular Open Systems Architecture (MOSA) to facilitate rapid assembly, integration, and test (AI&T), deployment, and operations of space assets into the current space architecture in operationally relevant timelines” [36]. This was an ambitious program designed to create a response architecture around the principle of providing just in time services that are “good enough” [36]. The main principle of the ORS program is its 3-tier response levels. Tier one solutions could be deployed in a matter of minutes to hours once a need is identified. This relies upon a playbook of government and commercial satellite services that can be acquired, reconfigured or re-tasked rapidly to meet an urgent need. Tier 2 solutions would utilize the MOSA to create a custom satellite using modular payload components that are assembled together to create a satellite that would be available for launch within days or weeks of the identified need. Tier 3 are solutions that would take up to a year from need identification to operational capacity being available [36].

This was an ambitious program that due to the current fiscal constraints of the DoD will more than likely be defunded. The program has seen some success in the last few years, namely the launch of the ORS-1 small satellite. The satellite was experimental and only designed to stay in orbit for one year. It was deemed successful [36].

Ideally, much of the research and development done for the ORS program could be transferable to HAP development; particularly in the application of their tiered response levels and MOSA payload components. Using the same principle of a depository of modular payload components that could be used to build out mission specific payloads and launch them on HAPs instead of satellites, operational needs could be met much faster than currently feasible. HAPs would not face the same cost and launch restrictions that exist in the satellite world.

C. BLUE FORCE TRACKING AND SEARCH AND RESCUE.

Blue force tracking has been heralded as a game changer for modern military operations. It provides commanders with real-time positional data of blue (friendly) forces. The system is not perfect. Not every soldier or element has one. Blue force trackers are typically one-way beaconing devices that transmit beyond line of sight using satellite-based receivers. This uses precious satellite resources and has increased in cost because of the need to lease commercial satellites as well. A HAP based network could aid in blue force tracking by integrating the feature into more end-user equipment like individual soldier radios. This would allow more forces to be tracked and relieve satellite bandwidth requirements.

HAPs could also aid in search and rescue. When a soldier becomes isolated, usually the only radio communication device he/she has left is their line of sight personal survival radio. These radios are limited by line of sight so contact can be delayed during the search phase of recovery until an air asset is in range of their radio. By using HAP compatible personal radios isolated personnel could initiate contact earlier and provide better positional information. This could aid in the speed of recovery.

D. OTHER COMBAT AND NONCOMBAT APPLICATIONS

Today's DoD is called upon for more than just wartime operations. Strategic defense, military exercises and humanitarian assistance and disaster relief (HADR) are common missions. Military exercises and strategic defense tend to create unique communications challenges of their own. HADR missions are typically performed in areas of severe communications degradations or destruction of local communications networks.

1. Humanitarian Assistance and Disaster Relief

For an example during the Haiti earthquake of 2010, a single HAP stationed overhead could have restored emergency communications to the entire area as well as providing critical data links for rescue and recovery forces. HAPs could be on station even before the actual forces arrive. Figure 25 displays the simulated coverage ring of a single HAP over Haiti.

Figure 25. Single HAP with 300 Km diameter coverage ring.

2. Ballistic Missile and Cruise Missile Defense

DARPA's Integrated Sensor is Structure (ISIS) program is intended to develop a radar that is integrated into the structure of Lockheed Martin's HAA platform. The radar is intended to provide constant ballistic and cruise missile identification and tracking from a HAP [37]. This program is the actual impetus behind Lockheed Martin's HAA program and is the core mission set for its design. The HAP technology being developed for this program has farther-reaching application than just this mission. Figure 26 is an artist representation of the ISIS HAA. As with many advances in military technology, the technology developed for a specific application or mission often has application in other areas. The ISIS and HAA airship programs are just one of those advances.

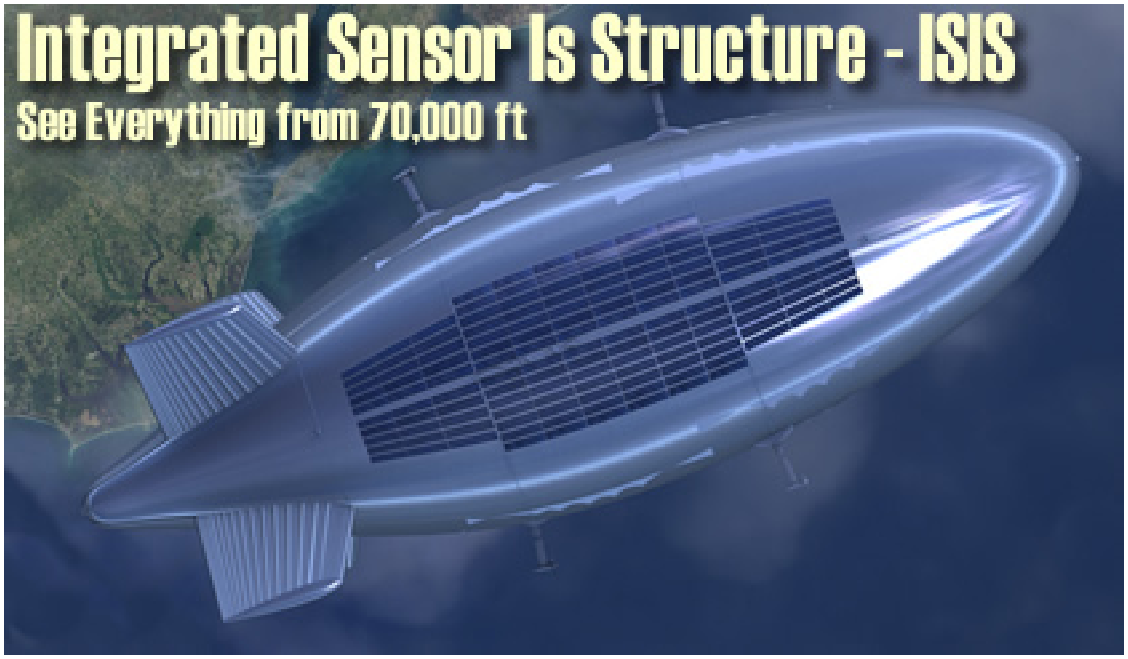

Figure 26. Artist's depiction of the ISIS HAA. From [37].

E. BATTLEFIELD AIRBORNE COMMUNICATIONS NODE (BACN)

The Battlefield Airborne Communications Node (BACN) program is a very similar concept to HAP based networking concept. Its intent is to extend the reach of a host of legacy and developing communications technologies.

> BACN was developed under a Department of Defense Microelectronic Activity contract (#H94003–04-D-0005), as part of the Interim Gateway Program. It provides a high-speed, Internet protocol (IP)-based airborne network infrastructure that that extends communications ranges, bridges between radio frequencies, and "translates" among incompatible communications systems – including both tactical and civil cellular systems. Using BACN, a Special Forces soldier on the ground could use a civil cell phone to speak to a fighter pilot in the cockpit.
>
> BACN supports seamless movement of imagery, video, voice and digital messages, with support for waveforms that include SINCGARS (single-channel ground and airborne radio system), DAMA (demand assigned multiple access), EPLRS (enhanced position location reporting system), SADL (situation awareness data link), Link 16, and IP-based networking connectivity using TTN (tactical targeting network), TCDL (tactical common data link) technology, CLIP (Common Link Integration Processing), and

> 802.11b. Northrop Grumman’s joint translator/forwarder (JXF), originally developed for U.S. Joint Forces Command, is [designed] to accomplish digital-message transformation.
>
> That kind of system can be especially useful in rugged terrain that [blocks] line-of-sight communications, in combined civil/military situations, or when different services or even different countries are operating side by side in the field. Afghanistan meets all of those criteria, and so do some aspects of operations in Iraq. [38]

The BACN system is currently deployed and supporting combat operations on a limited scale. The BACN system relies on several layered platforms to build out the network. Currently, the main platforms providing network coverage are three modified E-11A Global Express long-range business jets (one leased, two USAF-owned), and two (soon four) EQ-4B Global Hawk Block 20 UAV variants [38]. The system relies on Northrop Grumman’s joint translator/forwarder (JXF) as the gateway for legacy analog and digital line of sight (LOS) radio platforms into the wider area IP based network. Figure 27 is a picture of the current BACN payload.

Figure 27. BACN payload. From [39].

The system shows great potential for providing ubiquitous communications and data coverage throughout the battlefield, but current operating costs are high. The system currently relies on an airborne network of costly UAVs and manned aero assets maintaining 24-hour coverage above the battle space. Looking at the program in the context of this thesis, there appears an excellent opportunity for HAPs to fill the role of the current platforms. The E-11A platforms currently employed have a mission endurance of approximately 9 hours, and the EQ-4B Global Hawk Block 20 has a mission endurance of approximately 36 hours. HAPs could provide the same, if not improved, coverage with far less operational cost and improved availability since HAPs could stay aloft for weeks, months even years instead of hours with the current manned and unmanned platforms. This would greatly reduce the logistical footprint of the BACN support system and save substantial operating costs. Additionally, it would free valuable air assets for other high priority missions. Hence, a network of HAPs could substantially improve the availability of on station time of BACN while freeing up low density, high demand air platforms for higher priority tasking.

F. OPERATIONAL CONSIDERATIONS

When examining a technology or system for military application, the environment that it will potentially operate in must be considered. The operational considerations examined here are ground support requirements, combat survivability, and security. These are things that affect all of the systems discussed in this thesis; hence, they must be examined from the viewpoint of actually operating them in a crisis scenario.

1. Ground Support

As discussed in earlier chapters, HAPs offer the potential for reducing in-theatre support requirements because of their long endurance and coverage range. This is also true for long endurance UAVs such as the EQ-4B Global Hawk. From a military perspective, large terrestrial systems present a ground support problem because of basing requirements, the quantity of support equipment, and maintenance and force protection requirements. Many other comparisons can be made; however, this section compares ground support requirements between long endurance UAVs and HAPs. For support basing requirements, range and endurance of the platforms must be considered.

A HAP can potential support a mission for months, while UAV support is measured in hours. This significantly affects the basing requirements for the platforms. For example, a HAP that has a 6-month endurance could be deployed from the United States or other regional launching site. Limited forward maintenance facilities could be placed at strategic airbases around the world for emergency maintenance and regional support. With the reach of a domestically based fleet of HAPs, actual in theater support can be minimized or not required. This has many advantages for combat operations. It has been discussed previously that a HAP-based network could be deployed from the United States and be on station prior to combat forces even arriving.

The same cannot be said about current long endurance UAVs. While their range allows for their basing outside of the combat area, there is a requirement for a larger scale support network within the transit range for the UAV. Support functions such as refueling, maintenance, payload support and spare platforms would all have to be positioned much closer to the area of operations. The current standard for long endurance UAVs is the RQ-4 Global Hawk. Its flight endurance, depending upon configuration, averages 32 hours with a range of 8700 nm. In order to maximize coverage time within the desired area of coverage, staging bases must be established closer to the coverage area. This allows the operator to minimize transit times and maximize the time the platform can be on-station performing its mission. Comparing a HAP with a 6-month endurance to a UAV with a 32-hour endurance, the benefit of HAPs extended endurance is obvious.

Satellite based systems have the same advantages as HAPs. There is little in theater support for the main system. The support structure is limited to supporting the access equipment needed to connect to the satellite infrastructure. Because accessing satellite networks requires specialized and sometimes large equipment, there is a potential to reduce the required size of the user access equipment through the implementation of HAPs. This would be a benefit to the military forces in a combat area.

2. Combat Survivability

Combat survivability can mean different things to different people through the different levels of conflict. In a full-scale conflict scenario with a capable advisory, few systems are safe. Aircraft including manned, unmanned, and HAPS are susceptible to surface to air missiles systems commonly referred to as integrated air defense systems (IADS). Satellites are susceptible to jamming and missile systems as well. Ground based systems can only be defended within secured territory and are often considered high priority targets. So gauging combat survivability of a system is completely dependent upon the threat. Against most threats, we consider our satellite systems relatively safe because of their position in space. High altitude platforms would be difficult to target because of their altitude as well.

a. Electronic Attack

Electronic attack is actually a threat that is shared by both HAP-based and satellite systems. Electronic attack includes but is not limited to jamming, spoofing, and exploitation. Spoofing and exploitation fall more within the security topic that will be covered later. Jamming of electronic signals to deny the enemy the use of their systems is a common practice for most military forces. HAP-based systems have an advantage in this realm. Satellite-based signals, because of their distance from the earth, are relatively low powered by the time they reach the end user. HAP-Based signals have a much shorter distance to travel, therefore, they are much stronger at the receiver. This is key when considering the jamming power required to effectively degrade the communications. HAP-based transmissions are also much more localized. Referring back to the chapter three discussion on smart antennas, HAP based transmissions can be directional, therefore, reducing their susceptibility to jamming.

b. Security

Transmission security is an important consideration for communications systems, especially those supporting military operations. The techniques applied to existing military communication systems apply to HAP-based systems. Security concerns such as intrusion detection and denial of exploitation are well addressed in existing aerial-based communications systems; hence the technology is transferable to HAPs. The capability gap regards applying military security requirements to the commercial equipment envisioned for use on HAPs. This is beyond the scope of this thesis and is not covered here. It certainly is a worthy subject for future research.

G. SUMMARY

The technological advances being made under the HAA program could serve as the basis for more applications than just the ISIS program and Theater Missile Defense. HAPs can serve many roles both combat and non-combat related. In this chapter, several other missions were examined in which HAPs could play a vital role. These missions range from the communications mission that this thesis focuses on to intelligence gathering, blue force tracking, and support to humanitarian assistance and disaster relief operations. HAPs could also be integrated into existing missions that currently utilize shorter endurance platforms. HAPs could change and improve the way the DoD conducts a wide range of operations. The versatility of HAPs is limited only by the imaginations and creativity of the military decision makers that control their employment.

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VI. CONCLUSION AND RECOMMENDATIONS FOR FURTHER RESEARCH

A. CONCLUSION

This thesis explores the potential for HAPs to provide broad area wireless networking to support the concept of network centric operations by meeting its communications requirements during military operations. For the concept of broad area wireless networking via HAPs to develop, two key enablers must exist, (1) the aerial platforms themselves, and (2) the wireless data networking technology. To build the communications network, the HAPs need the performance capabilities required to conduct the mission. HAP development is ongoing and projects such as the HAA and ISIS are providing advances in platform design, system power supply, and payload support that could be leveraged for communications support missions. The commercial marketplace is developing high-capacity, long-range wireless data technologies such as WiMAX 2, MIMO, cognitive radios and smart antenna designs. Additionally, end-user equipment that is functional for military operations and is logistically easy to support, simple to operate, compact, mobile and reliable are all part of the wireless communications enabler. These technologies, while not initially designed for military applications, show potential for adaptation. Defense developers seeing the need for long-range wireless data connectivity are beginning to adapt these technologies and integrate them into military hardware, but the development is not widespread and is still being evaluated.

HAPs combined with advanced networking and communications systems are not intended to replace existing space-based and ground-based networking capabilities and should not be thought of as such. They are not competing network communications systems, rather, they are complementary technologies that can extend and enhance the capabilities of both space-based and terrestrial network communications systems in support of remote and often underserved areas. HAPs present a cost and operational advantage over space-based solutions to fill the existing communications gaps and shortfalls. Because of their long endurance, high altitude and mobility, HAPs can provide an economical and rapidly deployable communications capability into remote areas. A great deal of additional research remains on both fronts, but the concept shows promise toward meeting the goals of network-centric warfare.

B. ANSWERS TO RESEARCH QUESTIONS

This section addresses the research questions that were posed in Chapter I of this thesis.

1. Primary Research Question

Given the growing demand for wireless data and communications in modern military operations, could HAPs provide a robust and cost effective solution to distribute wireless data across an area of operations?

The answer to this question is overwhelmingly yes. HAP technology is advancing and nearing operational capabilities. The performance requirements (altitude, power, station keeping, and payload capacity) and design of the current HAA and ISIS projects are ideal for missions other than missile defense. The advances in wireless data transmission that are taking place in the commercial sector are relevant and transferable to military applications. The commercial demand for reliable high-speed wireless data networks provides the technology base for the development of military solutions. The demands of network centric warfare continue to show the vital need for the ability to move vast amounts of digital data around the battlefield. The thesis shows that HAPs are a great facilitator between existing and developing orbital infrastructures and the end-user providing enhanced throughput, lower cost and optimal propagation conditions that are superior to space based infrastructure.

2. Secondary Research Question 1

What existing or developing wireless technologies would be best suited to utilize for this application?

The IEEE recently ratified the WiMAX 2 802.16m protocol and the initial chipsets are entering manufacture. On paper, WiMAX 2 is ideally suited for the military application of HAPs in the broad area wireless data distribution mission. It is designed to provide up to 100 Mbits/s of data to highly mobile users and up to 1 Gbits/s to stationary users. This is more than adequate and far superior to existing technologies employed on the battlefield. The fact that it is optimized for IP data transmission makes it an ideal technology for bringing broadband wireless data to the battlefield. It also is designed to support digital voice services such as voice over IP and cellular telephone style communications. It shows the potential to be the backbone technology for a variety of data services that could support a wide range of data transmission needs.

3. Secondary Research Question 2

What services could be provided via HAPs?

Only the imaginations of system and equipment designers limit the services that could be supported by HAPs. HAP-based wireless networks could support a wide variety of telecommunications needs, voice communications, wireless data connectivity, intelligence collection, streaming video, blue force tracking and more. Services could be provided to highly mobile users down to the individual soldier and up to large fixed site operations centers. The wireless data connection is the key to fully developing the network centric warfare model and providing ubiquitous data connectivity to all echelons of the military.

4. Secondary Research Question 3

Do HAPs provide an operational and cost advantage over space-based and terrestrially based solutions?

Given the enormous expense and long lead times of developing, launching and operating space-based solutions, HAPs can provide enhanced connectivity and superior performance at lower costs. They have an advantage over terrestrially based solutions by greatly reducing the support footprint required within an area of operations. Terrestrial based solutions have shorter ranges and require a vast infrastructure that must be developed, maintained and defended. In many cases, terrestrial based systems are not feasible for combat theaters of operation, nor for remote areas and areas affected by a large-scale natural disaster. Rapid retasking of already in high demand space-based resources to provide additional coverage to remote areas or areas of emerging threats is complicated, costly, and likely has negative impacts on existing users. A HAP-based solution could be launched and in place within hours or days of an identified need or crisis with little to no in-theater support required. The combination of long endurance and position adjustability is one of the key advantages that HAPs have over space-based and terrestrially based solutions.

5. Secondary Research Question 4

Could HAPs be integrated into existing architectures and technologies?

Yes. By taking advantage of creative network design and the inherent flexibility of the proposed network architectures, HAPs could be integrated symbiotically with existing space-based and ground based systems. WiMAX 2 supports multi-radio access technology (Multi-RAT) integration and handoff; this allows existing technologies to be seamlessly integrated. Routing structures can be dynamic and support a wide range of architectures. HAPs could provide the bridge between separated ground stations while integrating both space-based and terrestrially based backhaul. This allows a HAP-based network to be designed to encompass existing resources. The HAP-based network could be rapidly reconfigured from one area of operations to another. This takes advantage of existing infrastructures or provides infrastructure establishment where none exists.

6. Secondary Research Question 5

What are the advantages and disadvantages of selected HAP-based network designs?

The three basic network designs discussed were the single HAP with onboard routing, multiple-HAP with onboard routing, and the more basic single-HAP with off-board routing. The single and multi-HAP designs with onboard routing would offer better network performance and improved flexibility, but this increases the complexity and power requirement for the HAP payload. These two network concepts would provide the greatest flexibility for network design by utilizing onboard routing of IP traffic. By using onboard routing the network could be completely independent and not rely on a local ground station. Reach back could be provided by HAP-to-satellite links or it could be setup as an air gapped, standalone network with no outside internet link. This design is more advantageous for military operations: it allows for the establishing of a wide area supporting tactical communications network prior to the arrival of a substantial ground force footprint in the theater of operations. In other words, it facilitates the initial phases of a military operation.

The single-HAP with off-board routing is the more basic design; it mirrors the satellite industry's current network design. Off-board routing requires a more substantial ground based gateway to handle the routing for the network; hence, it simplifies the equipment onboard the HAP. Its advantage lies in its simplicity, with its disadvantage being the increased in theater ground support required and the vulnerability that comes with that in a hostile theater of operations.

The decision of what network design to use is completely mission and is area of operation dependent. This flexibility provides the user with a great deal of freedom in tailoring services and connectivity as required. HAP-based networks can be designed to symbiotically integrate with existing infrastructures and provide communication and data transmission services to remote areas that are currently not feasible or impractical for current military capabilities.

C. RECOMMENDATIONS FOR FURTHER RESEARCH

This thesis has identified several areas that require additional research and exploration as the associated technologies develop and mature. The two key enablers listed in the conclusion consist of the aerial platforms themselves and the wireless data networking technology. The military industrial complex is currently pursuing development in the aerial platforms; therefore, this final section focuses on continued research into the data transmission side of the problem.

The thesis identifies WiMAX 2 as a potential technology for the development of the wireless infrastructure. With any military application, security of the data and the network is a key concern. Research needs to be conducted in the area of securing this kind of wireless data network so that it is compatible with the DoD’s network security requirements. Encryption is just one aspect of the security subject; features such as access control, frequency hopping, interference identification, jam resistance and intrusion prevention are all aspects of security that require addition research.

Additionally, since the WiMAX 2 standard is relatively new and available equipment is limited, research needs to be conducted into the actual performance capabilities of the technology. The design goals of 100 Mbits/s for highly mobile users and up to 1 Gbits/s for fixed users are only theoretically achievable. When equipment becomes available, field performance evaluations are needed to determine if the real world performance of the technology is in line with its theoretical design specifications (i.e., would the technology actually provide the level of connectivity required). Those evaluations would include testing the radio systems and the antenna designs for traditional and smart antennas. This thesis argues for filling in the frequently cited data transmission gap by taking advantage of the communications network performance increases that a HAP based network could provide when combined with the emerging advances in smart antenna and cognitive radio designs.

Equipment design is another area of future research. Because the WiMAX 2 standard is a commercial technology, the bulk of the hardware in development is intended for civilian applications. One of the advantages identified with adapting commercial technologies is the cost advantage over defense specific designs. This is highlighted in the MONAX™ system design that relies on COTS equipment with the addition of a military grade enclosure to provide ruggedness and system integration. Many manufactures do not design their equipment to mil-spec levels. That does not mean that COTS equipment is not suitable for military applications. In fact, recent examples, such as Lockheed Martin's MONAX™ system, demonstrate that COTS equipment is adaptable for military applications. This provides a significant cost advantage for the DoD, but equipment testing and ruggedization are required to adapt COTS equipment for military applications.

The following section outlines a discovery experiment to explore the capabilities and suitability of WiMAX 2 as the wireless data networking technology of choice for delivering broad area wireless data connectivity via HAPs.

1. Discovery Experiment

Broad area wireless networking via HAPs is a relevant area to explore. The following discovery experiment is proposed to further explore the concept of HAP-based wireless networking.

a. Design of Initial Discovery Experiment

Research and experimentation take a natural evolutionary step where theories and hypothesis must be taken out of the classroom and into the field. This section describes the framework for a discovery experiment involving HAP based networking.

> Discovery experiments involve introducing novel systems, concepts, organizational structures, technologies, or other elements to a setting where their use can be observed and catalogued. In the

DoD context, the objective is to find out how the innovation is employed and whether it appears to have military utility. [40]

The flexibility of the discovery experiment is that a trail could uncover interesting phenomena and change the trajectory of the experiment in the middle of events. Below is a description of a HAP based networking discovery experiment.

b. Experiment Scenario and Initial Plan

The discovery experiment explores the following research question:

How effective would a HAP-based high-speed wireless network be at fulfilling the projected data and communications needs tomorrow's deployed military forces?

The initial null hypothesis is: a HAP based wireless networking architecture would not provide any advantage over currently fielded long-range, high-speed data and communications to deploying military forces. Rejecting this null hypothesis would mean that HAP based networks are capable of bridging the capacity gap between demand and availability of satellite based and terrestrial based networking services.

For the purposes of the initial experiment, a high-speed wireless data/communications network would be built to cover an approximate area of 10,000 NM^2 miles utilizing two Aerostats at an altitude of 4,000 feet AGL.

The availability of functioning HAPs is very limited; therefore, to conduct the experiment, it is proposed to substitute low altitude tethered aerostats instead. That allows for much greater flexibility, reduced cost and ease of equipment management. The initial figure of 10,000 NM^2 of coverage is a rather arbitrary goal that should be theoretically possible based on the coverage footprint of two Aerostats stationed at 4,000 feet AGL. The maximum coverage area an aerostat at 4,000 feet AGL is 19010 NM^2.

With 2 Aerostats at 4,000' AGL the total theoretical coverage of an antenna at 4,000 feet AGL over a perfectly flat plane is 38,020 NM^2. The desired wireless technology for the experiment is the most recent revision of the IEEE 802.16m WiMAX 2 standard. The author hypothesizes that two Aerostats each carrying a WiMAX 2 base station, should provide approximately 5,000 NM^2 of network coverage each.

The initial experimentation plan is to deploy three WiMAX 2 base stations, 1 on each aerostat and then a third as a ground station. The ground station will act as the bridge between the wireless network and the rest of an established research network backbone. When the wireless network infrastructure is established, it will be connected to a network operation center (e.g., the Naval Postgraduate School's Center for Network Innovation and Experimentation (CENETIX) has a Network Operations Center (NOC) that regularly supports Tactical Network Topology (TNT) field experiments) to facilitate data collection necessary for analysis.

The Initial proposal is for running the experiment over a 72-hour period, three consecutive 24-hour experimentation cycles to be more specific. Each 24-hour period would be an independent experiment. Each 24-hour cycle would have a target 8-hour network operation window in which the network would be fully deployed and operational. During the 8-hour network operation window, there are many tasks to be accomplished, most notably are those associated with evaluating the established criteria constraints determined prior to the experiment. That operating window should allow more than ample time to run tailored simulations in order to evaluate those constraints. The operating window also allows time to evaluate and observe the function of the WiMAX 2 network during the routine network demands of the established research network. Following the network operations window the experimentation team would evaluate the lessons learned during the day's operations and determine any changes for the follow on day.

Each 24-hour period has different demands placed on the network and different network configurations. The purpose of the 3 days is to allow modifications to be made based upon discoveries from the previous day's work. Being a discovery experiment the simple explanation is that new configurations could be tried and evaluated each day based on performance issues that need fixing, or unforeseen opportunities to explore.

An integral part of the experiment is the deployment of various types of end user terminal equipment. The communications hardware used should vary from commercial cell phone style devices to military grade tactical transceivers. The purpose for this is twofold; first, to analyze the capacity of the devices, and second to create more realistic network loading. Some of this equipment could be distributed to other research participants to evaluate the ability to provide network access to distributed users. Their feedback on QOS would also be solicited as relevant data. Their utilization of the WiMAX 2 network as an extension of the existing network would be beneficial in providing additional network demand to aid in the performance evaluation of the networks stability and capacity.

c. Team Composition

Do to the nature of the experiment, the team should be comprised of several sub-teams. These sub-teams will have specific purposes and skills that are required in order to make the entire network function.

Overall experiment management team–An overall management team is require to coordinate the activities of all sub-teams as well as interact with TNT personnel for administrative and technical reasons. The management team should also contain an observation component for industry and government officials that are interested in the outcomes of the experiment.

Aerostat team–The aerostat team is in charge of the setup, deployment and operation of the aerostats. The primary composition of this team should be manufacturer technicians and service experts who are intimately familiar with the operation and control of the aerostats.

Wireless infrastructure team–This team should be manufacturer technicians familiar with the operation of the test hardware. Their role is to ensure that the hardware is functioning and properly configured. Their goals are to establish the network and maintain it.

Network performance team–This should be a separate and independent team of network performance evaluators. Their role is to evaluate the overall performance of the network while being unbiased and independent of any industry stakeholders.

Traffic simulation/observation team–This is the largest team. They operate user level equipment, services, handsets, laptops and tablets, etc. They are tasked with specific actions to conduct and evaluate as the experiment progresses.

d. Data Analysis and Collection Plan

Data collection is a combination of quantitative and qualitative measurements. Most of the network performance data can be recorded through established analytical software like OPNET or a similar application. The qualitative data is collected via a survey and interviews to determine QOS attributes. Sound clarity, stability and clarity of streaming video and the latency of VTC sessions are examples of qualitative observations that could be made.

The proposed schedule allows a limited amount to analyze the data and shape the next day's experiments. The rest of the analysis is done after the experiment.

e. Experiment Evolution, Transition Path to Campaign

Additional experimentations are suggested to test alternate wireless protocols, enhanced security layers, and various antenna designs. Those are just a few relevant subjects for additional testing. Eventually, an experiment that includes a working HAP with onboard routing that is integrated with space based platforms and routing such as IRIS could occur.

There is great potential in this concept; the first step is the initial proof of concept. By demonstrating the concept, the military utility can be evaluated and follow on experimentation can be justified. The most relevant capability to be demonstrated is that HAPs can fill in the capacity gaps better, faster and cheaper than space-based solutions [39].

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